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# Radiocolloidal Behavior of Some Fission Products*

**Some of the consequences of radiocolloid formation are explored. The authors summarize experimental results obtained by the techniques of dialysis, ultrafiltration, diffusion coefficient measurement and ion exchange, which illustrate the radiocolloidal behavior in solution of some of the radioelements which are formed from the fission of uranium**

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MANY INVESTIGATORS who have experienced difficulty in obtaining reproducible results with radiotracers are often unwilling observers of radiocolloidal phenomena. Knowledge of the conditions leading to the formation of radiocolloids—radiotracers which are present in minute concentrations and exhibit colloidal behavior—is important for the planning of many chemical, biological and physical experiments utilizing radiotracers and in the subsequent interpretation of the results.

Some of the experimental observations which exemplify radiocolloidal behavior are: (1) diminished diffusion velocity, (2) stratification in the presence or absence of centrifugation, (3) coagulation or peptization by electrolytes, (4) anomalous adsorption by ion exchangers, (5) adsorption, generally irreversible, upon finely divided matter or upon the walls of containing vessels, (6) incomplete exchange or lack of equivalence between radioactive and nonradioactive isotopes of the same element, (7) inability to dialyze through membranes permeable to ions in general, and (8) a discontinuous distribution of the radioactive matter as revealed by radioautographs.

Paneth observed radiocolloidal behavior in solution about 35 years ago when he dialyzed an aqueous solution of radiolead and found that only the lead isotopes passed through the membrane while the bismuth and polonium isotopes did not. Shortly after Paneth's work a large number of investigators established the presence of radiocolloids by methods such as electrophoresis, diffusion velocities, and centrifugation (*1, 2, 3, 4, 5*).

No adequate, or at least universally acceptable explanation of radiocolloid formation exists. The ordinary solubility product does not have to be exceeded as is illustrated by the classical case of the lead isotope, Th B. Paneth showed that Th B forms a radiocolloid at concentrations of about $10^{-11}$ mole per liter, even though $10^{-5}$ mole per liter is necessary to attain the solubility product. Paneth (*1*) and others hold the opinion that radiocolloids are true colloids even though "it is by no means clear how these substances in such low

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* Part of the material in this paper was presented by one of the authors (J. S.) before the Division of Colloid Chemistry of the American Chemical Society, at the 113th national meeting in Chicago, Illinois, April, 1948. A preliminary report of this work, AECD 1910, was made available by the U. S. Atomic Energy Commission.

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concentrations can form a solid phase, unless it be assumed that they possess an abnormally small solubility product." Zsigmondy and Hahn (*2*), on the other hand, believe that the concentration of many carrier-free radioelements is too small to permit the formation of an independent colloidal phase. According to the latter view, "the radioactive ions are adsorbed upon solid impurities accidentally present in the solutions, thereby imitating a colloidal character, and form in the so-called 'radiocolloids.'" Several studies have been made to test the effect of impurities on radiocolloid formation but the results of different investigators are generally regarded as inconclusive.

In terms of number of molecules it is possible for radiotracers to form particles of colloidal dimensions. For example, on the assumption that radiocolloidal Cb exists as particles of $Cb_2O_5$ with diameters of $10^{-6}$ cm it is calculated that, in a solution about $10^{-11}$ molar in $Cb_2O_5$, there can exist about $10^6$ of these colloidal particles per cc, with each such particle consisting of $10^4$ molecules. If hydration effects were considered, even less $Cb_2O_5$ would be required to form such radiocolloids. Similar reasoning was employed by Kurbatov and Kurbatov (*4*) with regard to the radiocolloids of Po, Pb, and Bi. Furthermore, it appears that the coagulation properties, observed with particles having the apparent dimensions of radiocolloids, may be anticipated from semi-quantitative considerations based upon von Smoluchowski's equations which deal with the kinetics of flocculation (*21*). The pertinent question seems to concern, therefore, the probability with which individual molecules of a tracer combine to form particles of colloidal dimensions.

Experiments on the factors involved in the formation of radiocolloids in gaseous media by Harrington (*6*, *7*) and Chamié (*8*) provide convincing evidence for the thesis that nuclei (not necessarily dust) are needed to induce radiocolloidal formation. By methods involving centrifugation, radioautography, and direct ultramicroscopic observation, Harrington investigated the aggregate formation in tubes in which were sealed radon and various gases. In every case studied, aggregates, *i.e.*, radiocolloids, formed from decay products of radon, were obtained when the mixture contained polar molecules, but none were detected when only nonpolar molecules were present. Thus, for example, aggregates were formed in the presence of moist air, hydrogen chloride and chloroform, and not formed in mixtures containing dry air or carbon tetrachloride. These experiments, and those of Mlle. Chamié (*8*) indicated that the extent of aggregate formation was a function of the electric moment of the polar molecules in the radon mixtures.

The formation of the aggregates was explained by Harrington on the following basis: the ions and recoil atoms present in the mixture as a result of the ionization action of radiations and of radioactive disintegrations tend to remain together upon collision, particularly when two or more atoms of radioactive or other substances normally existing as a solid under the conditions of the experiment are included in the ionic cluster. A certain proportion of the polar molecules would be expected to remain in the resulting group because of the tendency of such molecules to become adsorbed on solids. The chance of further acquisitions increases with the growth of the aggregate. An aggregate once formed would continue to grow until removed through the action of gravity or by adsorption on the walls of the containing vessel.

Because of the very small number of radioactive atoms actually present rela-

tive to the number of other molecules present it would appear that polar molecules definitely favor, and are possibly essential in, the formation of radiocolloids in gaseous mixtures containing radon. The magnitude of the effects observed increase with the number of atoms of active deposit, and on the concentration of polar molecules. This is in agreement with the experimental facts.

Considerations, analogous to those described above, could explain the formation and properties of radiocolloids in solution (*8*). Presumably then, a polar solvent aids, or is necessary for, the formation of radiocolloids in a liquid medium. Experiments to test this point should prove of great interest.

According to Harrington's theory, it would appear that radioactivity and ionization phenomena are not only necessary but may initiate the formation of radiocolloids. Such a possibility has been considered by Paneth and others. Definitive answers to this question and others concerning radiocolloid formation await further experimental investigations.

Whether or not radiocolloids are "true" colloids does not alter the description of the properties associated with them. While it is difficult to always obtain quantitatively reproducible data relating to radiocolloids, the conditions under which they are formed and their subsequent properties are qualitatively reproducible and predictable. As a rough working rule one can state that a radiotracer is likely to become a radiocolloid if its solubility in a given medium is reduced to such a point that precipitation, agglomeration, or opalescence would be observed. On this rather intuitive basis, then, it is apparent that radioelements of Na, Ba, and La, for example, as well as easily hydrolyzable elements such as Zr, Pb, and Bi, may form radiocolloids.

## EXPERIMENTAL RESULTS

### Dialysis of Fission Products

In a solution of uranyl nitrate at its natural *p*H and containing most of the fission products, only Zr and Cb do not dialyze completely. In our experiments the solution to be dialyzed was contained in a bag or thimble constructed of "Visking" or parchment membranes. The procedure ordinarily followed was to carry out the dialysis with solutions of identical chemical composition in both compartments but differing in that the solution within the membrane contained the radioactive constituents under examination. The solutions in both compartments were stirred constantly. The volume of the solution outside the dialysis bag was ten times that contained in the bag. Experiments on the rate of dialysis under conditions in which the outer solution was not renewed showed that equilibrium was practically attained in 24 hours. At the end of the dialysis period both solutions were sampled, analyzed radiochemically and material balances computed.

The data in Table I summarize some of our findings. It is seen that the addition of nitric or sulfuric acids to uranyl nitrate increased the dialysis of zirconium and columbium. In the case of Zr the increased dialysis is due to the hydrogen ion as evidenced by the ineffectiveness of sodium nitrate or sodium sulfate. The sulfate ion increased the extent to which Cb dialyzed. Larger concentration of sulfuric acid, *i.e.*, $> 3M$ should probably have an even greater effect since it appears that columbium eventually forms a stable complex with sulfate ion (*9*).

The effect of different reagents on the dialysis of Zr, Cb, and La is shown in Table 2. The results show that $F^-$, $C_2O_4^=$, $PO_4^=$ and $H^+$ increased the dialysis of Zr and Cb while $F^-$ and $C_2O_4^=$ decreased the dialysis of La.

**TABLE 1**

**Dialysis of $Zr^{95}$ and $Cb^{95}$ in Uranyl Nitrate Solution, $t$ = 50° C**

| *Composition of Solution (Moles/Liter)* | | | | | *Percent Dialyzed* | |
|---|---|---|---|---|---|---|
| *Uranyl Nitrate* | *Nitric Acid* | *Sulfuric Acid* | *Sodium Sulfate* | *Sodium Nitrate* | $Zr^{95}$ | $Cb^{95}$ |
| 0.48 | 0 | 0 | 0 | 0 | 30 | 22 |
| 0.48 | 0 | 0.5 | 0 | 0 | 100 | 80 |
| 0.48 | 0 | 0 | 0.5 | 0 | 18 | 74 |
| 0.48 | 0.5 | 0 | 0 | 0 | 66 | 77 |
| 0.48 | 0 | 0 | 0 | 0.5 | 15 | (22) |

These findings are compatible with the known complexing action of fluoride and oxalate ions toward Zr and Cb. Likewise, the insoluble nature of the fluorides, oxalates, and phosphates of $La^{+3}$ and other members of the rare earth group of cations are well known. The chemical concentration of La in these solutions (undetectable by spectrographic analysis) was well below the amount required to exceed the apparent solubility products of either its oxalate or fluoride salts.

### Ultrafiltration

Ultrafiltration* is a more rapid and convenient method than dialysis for the study of the diffusibility of radiotracers. The apparatus illustrated in Fig. 1 is a modification of a type used by Greenberg and Greenberg (*10*). The sacs used were made of "Visking" cellulose casing.† They are impermeable to proteins. About 1½ hours of constant suction yields about 1 ml of diffusate.

A convenient universal buffer for use in ultrafiltration studies is the veronal buffer devised by Michaelis (*11*). This buffer, which consists of a mixture of sodium acetate, sodium diethylbarbiturate, and hydrochloric acid, has the advantage of not forming insoluble salts with most of the fission products.

The effect of *p*H on the ultrafilterability of polyvalent hydrolyzable cations is schematically shown in Fig. 2. The *p*H which just precedes a sharp drop in diffusibility corresponds, in general, to the *p*H at which precipitation of macroscopic concentrations of the cation are observed. The extent of the drop appears to be related to the complexing strength of the buffer anions relative to a particular cation. Some adsorption ($\sim$ 10% of the total) takes place on the membrane itself. The radioelements appear to be in

**TABLE 2**

**Effect of Various Reagents on the Dialysis of Carrier-Free Fission Products, $t$ = 25° C**

| *Bulk Electrolyte* | *Concentration (Moles/Liter)* | *Percent of Fission Product Dialyzed* | | |
|---|---|---|---|---|
| | | $Zr^{95}$ | $Cb^{95}$ | $La^{140}$ |
| $H_2O$ | — | — | — | 100 |
| HCl | 0.01 | (25) | 21 | 100 |
| $HNO_3$ | 1.0 | — | 74 | 100 |
| $H_3PO_4$ | 0.1 | 47 | 74 | 93 |
| $H_2SiF_6$ | 0.1 | 100 | 100 | 66 |
| $H_2C_2O_4$ | 0.1 | 47 | 80 | 26 |

* The authors wish to acknowledge the assistance of David Revinson in these experiments.

† The "Visking" was 1⅛ inches in diameter and the manufacturer size rating was $\frac{23}{32}$. It may be purchased from the Visking Corporation, 6733 West 65th Street, Chicago, Illinois.

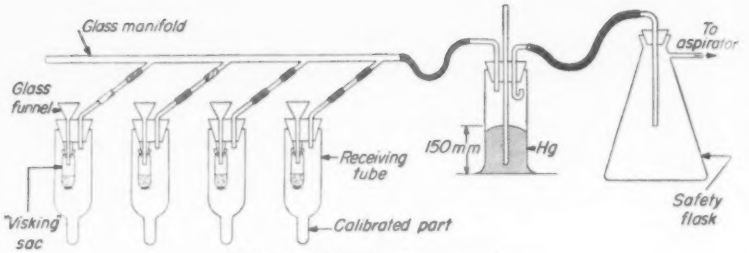


**FIG. 1. Ultrafiltration apparatus**

adsorption equilibrium with the membrane since a considerable fraction of the ultrafiltrate, obtained at a *p*H where the diffusibility was low, is still retained by the membrane. This result is analogous to the findings of Kurbatov and Kurbatov (*4*). In their experiments they filtered carrier-free $Y^{86}$ at alkaline *p*H's through two consecutive filter papers. The second filter paper also retained $Y^{86}$, though to a lesser extent than the first.

When human urine, at its natural *p*H of 6.2, was spiked with Pu(IV) it was found that 52% of the added Pu was diffusible. When the *p*H of the urine was reduced to 2.1 by addition of hydrochloric acid, the percent of diffusible Pu increased to 80%.

Only a small fraction, 25% or less, of plutonium is ultrafilterable from human blood serum or plasma (*12*). Such a finding is not necessarily due to a combination of Pu with proteins because dialyzed serum or plasma gave the same results. It is known that Pu has a very strong tendency to become hydroxylated and thus to undergo polymerization (*13*).

The adsorption of tracer Pu(IV) by glass surfaces was shown by King (*14*). The adsorption increased as the *p*H was increased but an appreciable adsorption was observed in 0.02*M* $HNO_3$. Centrifuging experiments conducted at different acidities also demonstrated the radiocolloidal properties of Pu(IV). On the other hand, neptunium (V) did not show radiocolloidal characteristics even at hydrogen ion concentrations of $10^{-4}$ molar (*14*). It further appears that Pu(V) would parallel Np(V) in this case.

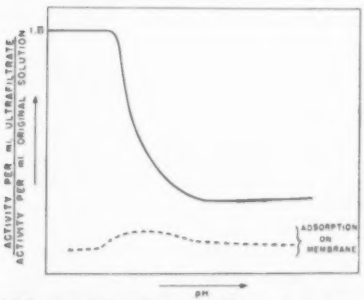


**FIG. 2. The effect of pH on the ultrafilterability of a hydrolyzable radioelement**

### Diffusion Coefficient Measurements

The measurement of the diffusion coefficient yields considerable information about the state of an element in solution. Diffusion measurements were employed by Paneth and Hevesy (*15*) as a means of determining the valence of radioelements and of detecting radiocolloidal behavior in some of the naturally occurring radioisotopes of Ra, Bi, Po, Pb, Th, and U. The accounts of these experiments deserve a careful reading. In the experiments reported here, the diffusion coefficients of radiotracers from uranium fission

## TABLE 3

**The Diffusion Coefficients*† of Carrier-Free Fission Products in Uranyl Nitrate and Acid Solutions at 25° C**

| *Composition of solution (moles/liter)* | | | | *Diffusion coefficient,* D, *in cm²/day* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Uranyl Nitrate* | *Nitric Acid* | *Sulfuric Acid* | *Viscosity‡ of solutions (millipoises)* | $Ba^{140}$ | $Sr^{89}$ | $La^{140}$ | $Zr^{95}$ | $Cb^{95}$ | $Ru^{103}$ | $Te^{127}$ |
| 0.48 | 0 | 0 | 11.8 | 0.37 | — | 0.35 | 0.22 | 0.22 | — | — |
| 1.2 | 0 | 0 | 18.9 | 0.25 (0.23) | 0.24 | 0.23 (0.22) | 0.13 (0.14) | 0.11 (0.14) | 0.27 | — |
| 0.48 | 0.5 | 0 | — | 0.57 | — | *ca* 0.5 | — | — | — | — |
| 0.48 | 0 | 0.5 | 13.35 | 0.15 (0.33) | 0.34 (0.34) | 0.31 (0.31) | 0.81 (0.19) | 0.21 (0.19) | — | 0.70 |
| 0 | 0.235 | 0 | 9.07§ | 0.61 | — | 0.53 | — | — | — | — |
| 0 | 1.2 | 0 | 9.3§ | — | — | 0.51 (0.52) | — | — | — | — |
| 0 | 5.0 | 0 | 12.2§ | — | — | 0.45 (0.40) | — | — | — | — |

* The values in parenthesis were calculated by assuming that $D$ was inversely proportional to the macroscopic viscosity.
† The average deviation for duplicate runs was about ±5%.
‡ Measured directly with an Ostwald viscosimeter.
§ Estimated from data in "International Critical Tables," Vol. V, p. 13 (McGraw-Hill Book Company, Inc., New York, 1929).

were measured under conditions where the composition of the bulk electrolytes in both the upper and lower cells of McBain-Northrop sintered-glass diaphragm cells was identical except for the presence of $\sim 10^{-10}M$ of radiotracer in the upper cell. The techniques, calculations and calibration procedures employed were essentially those described by McBain and Liu (*16*). Before use, all solutions were filtered through a fine fritted glass filter funnel. A preliminary diffusion with inactive solutions for three hours was always carried out to establish equilibrium conditions. Diffusion was continued until approximately 5% of the tracer had diffused. Radiochemical analyses of the original solution, and of the contents of the upper and lower cells after diffusion were made so that material balance checks could be obtained. Counting was done with a mica-window Geiger-Müller tube and a scaling circuit.

The diffusion coefficient of the radiotracers in our experiments was, in the main, directly proportional to the macroscopic viscosity (Table 3) as would be expected from the fact that the measurements were made in a large excess of electrolyte, *i.e.*, charge effects are nullified and the ions or colloidal particles diffuse independently (*17*, *18*).

The viscosity correction does not seem to apply to the diffusion of Ba and Zr in a mixture of uranyl nitrate and sulfuric acid. This finding is readily explainable. The $Ba^{++}$ has reacted with the sulfate ions to form a radiocolloid. The ionic nature of $Sr^{++}$ in the presence of sulfate ion is presumably due to the fact that the solubility product of $SrSO_4$ is about $10^4$ times

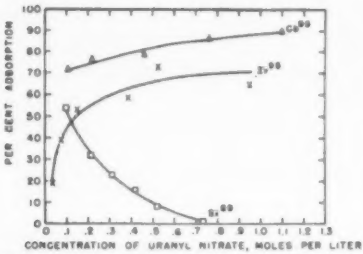


**FIG. 3. Adsorption of carrier-free $Zr^{95}$, $Sr^{89}$, and $Cb^{95}$ by the uranyl form of the cation exchange resin, Amberlite IR-1. Ratio of the volume of solution to the weight of air-dried $UO_2R_2$ was 100/1 for Zr and Cb adsorption and 25/1 for Sr adsorption**

greater than that of $BaSO_4$. The Zr, on the other hand, which was in a predominantly radiocolloidal state was complexed by the sulfate ions to form a soluble anion. Thus, from the absolute value and change in $D$ of a radiotracer following a change in environment we gain information regarding its state in solution.

The low values for Zr and Cb are indicative of their ubiquitous radiocolloidal states. Actually the values reported are probably too high because of removal of part of the tracer on the glass membrane during the preliminary filtration procedure.

Inasmuch as our diffusion measurements were made in a large excess of electrolyte it is possible (*17*) to apply the Einstein-Stokes equation in order to calculate the radii of the tracer radioelement. The radius of a suspended substance in solution is given by the Einstein-Stokes relation,

$$D = \frac{RT}{6\pi\eta r N} \qquad (1)$$

in which $D$ is the diffusion coefficient, $R$ the gas constant, $T$ the absolute temperature, $N$ Avogadro's number, $r$ the mean radius of the particles, and $\eta$ the viscosity of the medium.

Applying Eq. 1, we find that the radius of either Zr or Cb in 0.48$M$ or 1.2 uranyl nitrate is about 8–10 A.U.

It is of interest to note that the ratio of colloidal to ionic fractions of a radioelement present in a solution, as determined by the aforementioned sintered glass technique, is in complete agreement with the results of ultrafiltration measurements.

It has been shown that radiocolloids can be studied with the synthetic resin cation exchangers (*19, 20*). Inasmuch as the uptake of cations by a cation exchanger is governed by mass action principles, an increase in the cationic concentration of a solution should diminish the adsorption of a tracer cation. The adsorption of tracer Cb, and Zr, however, has been found to increase when the bulk cation concentration is increased. In the latter case the tracers are not adsorbed by the usual cation exchange mechanisms. Instead the bulk electrolyte acts as a coagulating agent and the resin functions as an adsorbent. The data in Fig. 3 illustrate the adsorption of a cation, $Sr^{++}$, contrasted with that of the radiocolloids of Zr and Cb when the concentration of the bulk electrolyte, uranyl nitrate, is increased. Observe how the difference in adsorption between a radiocolloid and a cation can be used to effect a simple and clean separation of the two.

A convenient index for differentiating cation exchange adsorption by a cation exchanger from colloidal type of adsorption is the equilibrium distribution coefficient, $K_d$, which is given by the expression:

$$K_d = M_s/M_l \times \text{volume of solution/mass of resin} = M_s/M_l \times v/m \qquad (2)$$

in which $M_s$ and $M_l$ are the fractions of the adsorbed radiotracer, $M$, in the resin and liquid phases, respectively. Equation 2 may also be written as:

$$K_d = \frac{\%\ \text{adsorbed}}{100\% - \%\ \text{adsorbed}} \times \frac{v}{m} \qquad (3)$$

In a true cation exchange process it has been shown that (1) $K_d$ is constant when $v/m$ is varied; (2) $K_d$ decreases when the bulk electrolyte concentration is increased; and (3) $K_d$ decreases upon the addition to the solution of a complexing agent which forms an unadsorbed (*i.e.*, neutral or negatively charged) complex ion with the cation or radiocolloid. The decrease in $K_d$, in this case, is proportional to the concentration of added complexing agent.

When radiocolloidal adsorption is encountered the $K_d$ varies directly with changes in $v/m$ and may remain nearly constant or even increase when the bulk electrolyte concentration is increased. The irreversibility of radiocolloidal adsorption is also marked. A fuller discussion of these points together with extensive experimental data is given in reference (*20*).

A rapid and reliable criterion for differentiating cations from radiocolloids is to note the extent of adsorption of a tracer from high concentrations of bulk electrolyte. It is often found that there exists a concentration of bulk electrolyte in which no cation, regardless of valence, is adsorbed to more than a few percent; yet as much as 50–90% of a radiocolloid under the identical conditions would be adsorbed.

Now that some of the characteristics of radiocolloids have been shown it is of interest to show how such knowledge may enter into some types of investigations.

The solubility product of radium sulfate, as determined by Lind and coworkers (*22*) was found to be too low by a factor of about 67 by Erbacher and Nikitin (*23*). In Lind's experiments the insoluble matter was separated from solution by filtration through cotton. It turns out that more than 98% of the dissolved radium was adsorbed upon the cotton filter. This radiocolloidal behavior of $RaSO_4$ is quite reasonable in view of the behavior of $BaSO_4$ as discussed earlier in this paper.

Many biological experiments utilize a phosphate buffer. The use in such systems of tracer radioelements having a tendency to form insoluble phosphates must proceed with caution. This is of particular importance when adsorption or diffusion characteristics of the tracer are involved. Further difficulties are encountered when the behavior of hydrolyzable radioelements are studied. In the physiological *p*H ranges practically all the trivalent and tetravalent metal cations are probably polymerized to some extent—unless they are completely complexed by anions such as citrates and carbonates. For example, upon the ultrafiltration of Pu(IV) from blood serum, inability of the Pu to pass the membrane might lead to the conclusion that all of the radioelement was bound to the serum proteins. However, in the absence of proteins, (dialyzed serum or plasma) but at the same *p*H as blood serum, similar results are obtained (*12*).

In studies of the distribution and excretion rates of radiotracers it is necessary to consider possible radiocolloid formation in the injection solution. The relative rate of uptake by rat tissues of several radioelements was found to be a function of their diffusibility (*24*). In this connection, it is of interest to note that in 1917 Schulemann (*25*) showed that the rate of distribution of several dyes subcutaneously injected into mice or rabbits was directly related to their relative rates of diffusion as measured in gelatin.

In experiments where a tracer is added to macroscopic concentrations of the same element, it is often very difficult to obtain equivalence between the tracer and its presumably macroscopic counterpart because of the irreversible characteristics of the radiocolloid. Thus, if tracer Zr is added to

even a strongly acid solution of a zirconium salt it is necessary to subject the solution to a series of chemical reactions in order to obtain complete identity between the radiozirconium and its nonradioactive isotopes. This can be accomplished by complexing the mixture, then breaking the complex, and repeating, or by refluxing the solution in a concentrated mineral acid for several hours (*26*).

Many times it is desired to minimize adsorption of tracers on the walls of containing or receiving vessels. In view of the discussion given in the preceding paragraph it would not always be advisable to trust to mere saturation of the surfaces with nonradioactive carrier isotopes. It is well known in radiochemistry that the addition or presence of complexing agents is the most reliable means of minimizing or eliminating such adsorption. Thus, a small amount of oxalic or hydrofluoric acid will eliminate the colloidal properties of Zr or Cb, while citric acid at a *p*H of about 4 is of general usefulness for numerous polyvalent cations.

The formation of discontinuous aggregates as shown by radioautographs enters, for example, into studies of the distribution of tracers in amalgams (*27*) and minerals (*28*). The presence of radiocolloid aggregates in the uranium mineral, uraninite, was shown recently by Yagoda. When aggregates exist the radioautograph reveals a black core surrounded by a halo of radiating tracks produced by alpha particles striking the emulsion at glancing incidence. [This result is similar to some recently reported studies in which the radioautographs of a dilute ionic solution of polonium, suddenly frozen, showed the existence of colloidal aggregates (*29*).] It was estimated that as a result of radiocolloid formation the radium was concentrated 150-fold over that normally present in equilibrium with uranium. It is apparent that the formation of radiocolloidal aggregates could affect the accuracy of determinations of the age of minerals.

The conditions and time of storage of a tracer having radiocolloidal tendencies may affect its chemical behavior, particularly in view of the rate phenomena involved. This will be true even in cases where the tracer is subsequently diluted with a great excess of electrolyte. An example was shown (*20*) by an experiment in which one sample of carrier-free $Zr^{95}$ was stored in 10*M* HCl and another sample was stored in 1*M* HCl. About 0.01 ml of the tracer which was previously stored in 10*M* HCl was added to 25 ml of 0.4*M* uranyl nitrate and was found to be cationic in nature as indicated from the results of ion exchange experiments, while the $Zr^{95}$ which had been stored in 1*M* HCl behaved as a typical radiocolloid under similar conditions.

* * *

*Most of the experiments described in this paper were done in the Chemistry Division of Clinton Laboratories at Oak Ridge during 1944–45 under the general direction of G. E. Boyd. The authors are indebted to William B. Leslie for his assistance in the performance of many of the dialysis experiments.*

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This betrayal of the scientist by his armamentarium is no new problem. About 1850, for example, the French scientist Chatin developed a micromethod for measuring iodine. He applied it in a comprehensive study of the waters of the various valleys of the Rhone, the Seine, and other rivers of France. Out of this work he drew the surprisingly clear statement that the principal cause of goiter and cretinism was an insufficiency of iodine. Moreover, he went on to say that it would be a simple matter to reinforce the deficient sources of water supply with mineralized solutions of iodide. His fellow scientists tried to apply his method and failed. Finally, the French Academy surveyed these results and concluded that Chatin's work was not tenable. The poor man ended his career in disappointment and frustration; and the world remained indifferent to this important etiological factor in goiter until in rather recent decades the work of Marine, McClendon and others eminently confirmed Chatin's hypothesis.

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even a strongly acid solution of a zirconium salt it is necessary to subject the solution to a series of chemical reactions in order to obtain complete identity between the radiozirconium and its nonradioactive isotopes. This can be accomplished by complexing the mixture, then breaking the complex, and repeating, or by refluxing the solution in a concentrated mineral acid for several hours (*26*).

Many times it is desired to minimize adsorption of tracers on the walls of containing or receiving vessels. In view of the discussion given in the preceding paragraph it would not always be advisable to trust to mere saturation of the surfaces with nonradioactive carrier isotopes. It is well known in radiochemistry that the addition or presence of complexing agents is the most reliable means of minimizing or eliminating such adsorption. Thus, a small amount of oxalic or hydrofluoric acid will eliminate the colloidal properties of Zr or Cb, while citric acid at a *p*H of about 4 is of general usefulness for numerous polyvalent cations.

The formation of discontinuous aggregates as shown by radioautographs enters, for example, into studies of the distribution of tracers in amalgams (*27*) and minerals (*28*). The presence of radiocolloid aggregates in the uranium mineral, uraninite, was shown recently by Yagoda. When aggregates exist the radioautograph reveals a black core surrounded by a halo of radiating tracks produced by alpha particles striking the emulsion at glancing incidence. [This result is similar to some recently reported studies in which the radioautographs of a dilute ionic solution of polonium, suddenly frozen, showed the existence of colloidal aggregates (*29*).] It was estimated that as a result of radiocolloid formation the radium was concentrated 150-fold over that normally present in equilibrium with uranium. It is apparent that the formation of radiocolloidal aggregates could affect the accuracy of determinations of the age of minerals.

The conditions and time of storage of a tracer having radiocolloidal tendencies may affect its chemical behavior, particularly in view of the rate phenomena involved. This will be true even in cases where the tracer is subsequently diluted with a great excess of electrolyte. An example was shown (*20*) by an experiment in which one sample of carrier-free $Zr^{95}$ was stored in 10*M* HCl and another sample was stored in 1*M* HCl. About 0.01 ml of the tracer which was previously stored in 10*M* HCl was added to 25 ml of 0.4*M* uranyl nitrate and was found to be cationic in nature as indicated from the results of ion exchange experiments, while the $Zr^{95}$ which had been stored in 1*M* HCl behaved as a typical radiocolloid under similar conditions.

* * *

*Most of the experiments described in this paper were done in the Chemistry Division of Clinton Laboratories at Oak Ridge during 1944–45 under the general direction of G. E. Boyd. The authors are indebted to William B. Leslie for his assistance in the performance of many of the dialysis experiments.*

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# Comparative Survey of Ion Guns—II

**Canal-ray, low-voltage capillary, focused electron-beam, and high-frequency ion sources are among the representative sources discussed in this second of a series of three papers**

By MAX HOYAUX and IGNACE DUJARDIN

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*Ateliers de Constructions Electriques de Charleroi, Belgium*

HAVING THUS REVIEWED the broad requirements for ion guns, we are in a position to examine the means whereby these ideals are approached. The ion sources described in the literature are generally of the following four types:

1) high-voltage canal-ray ion sources,
2) low-voltage capillary-arc ion sources (with a probe),
3) ion sources with oscillating electrons and magnetic focusing,
4) high-frequency ion sources.

## CANAL-RAY ION SOURCES

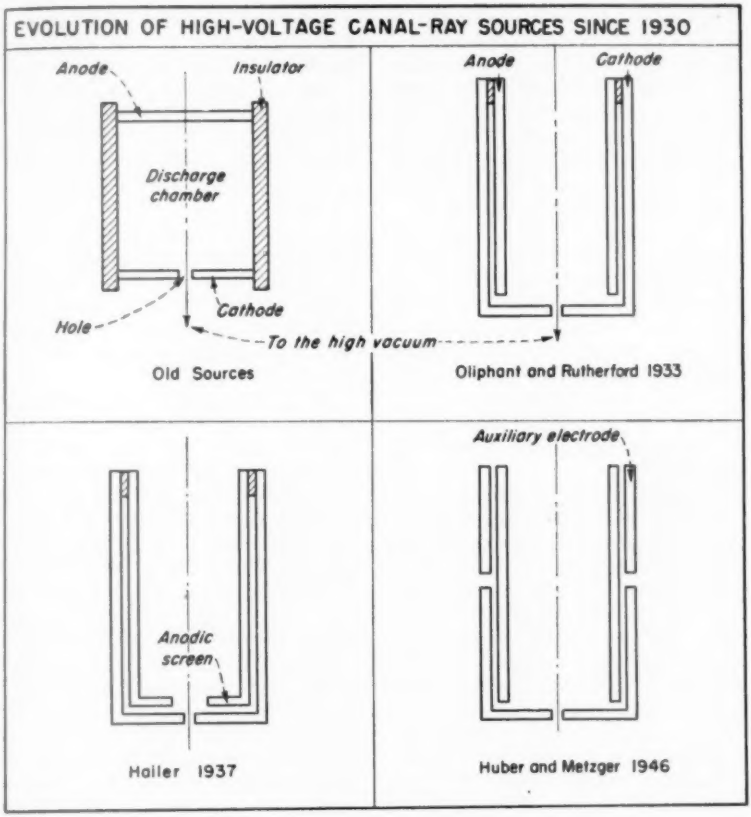
The oldest ion source is probably the one used by Thomson in 1913 for the first mass spectrograph. It consists of a large spherical discharge space with an anode in a side arm, and a big cylindrical cathode along the axis. The hole of the cathode has a diameter of several millimeters and a length of several centimeters. Some 30 to 50 kv are applied between anode and cathode. Very little information can be obtained about the performance of Thomson's ion source. Probably a very small fraction of one microampere was available. Had a difference of pressure been maintained between the two faces of the cathode, the gas flow would have been very high. Owing to low dimensions of the utilization chamber, this was fortunately not the case.

With the birth and growth in importance of accelerating devices, many investigators searched for improved ion sources. Canal-ray ones were improved in two different directions: (a) high voltage cold-cathode sources, with concentric cylindrical electrodes; in these the cathode is terminated by a bored plane, through which the canal-ray passes, and (b) low voltage hot-cathode sources, with an auxiliary perforated electrode beyond the cathode, generally very negative with respect to it, the hole allowing passage of ions into the high vacuum accelerating chamber. The former type, first developed by Oliphant and Rutherford in 1933, is still much used today. The latter, first described by Lamar and Luhr in 1934, seems to have been almost discarded since 1938.

### High-Voltage Sources

**Source of Oliphant and Rutherford**—As early as 1933, Oliphant and Rutherford (*1*) described a very important improvement of Thomson's high voltage ion source, which gave them hydrogen ion currents from 20 up to 1000 $\mu$a. Previously, Cockroft and Walton (*2*)

**Editor's Note:** The three papers in this series combine a description and comparison of some kinds of ion guns which have been described in the literature since Thomson's experiments in 1913. In the first paper [see NUCLEONICS 4, No. 5, 7 (1949)], the general properties and specific characteristics of typical guns were discussed. In close connection with the subject of ion sources described in the second paper, appearing here, the third paper, to be published next month, reviews the necessary refinements of ion-gun design.




and others used canal-ray ion sources in which a discharge of some 20 to 50 ma was maintained under a voltage drop of some 20 to 50 kv between plane electrodes, the cathode of which was perforated. Ion currents from 1 up to 100 $\mu$a had been produced in that way, generally with high gas consumption (this was not a striking difficulty because it was low-priced hydrogen) and high pumping speed.

These currents struck the target after 90° magnetic deflection, which gave beam analysis; no other focusing device was provided.

Oliphant and Rutherford used two concentric cylinders as electrodes, the cathode being terminated by a perforated plane. Those cylinders had a length of 1 meter and one had a diameter of about 12 cm.

The side clearance is so thin that no lateral discharge can start according to Hittorff's condition. The discharge is actually maintained between the inner part of the cylindrical anode and the central area of the plane part of the cathode. Visual observations show that the cathode glow appears as a luminous pencil along the axis of the



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source. Its diameter generally does not exceed several millimeters. It is evident that, if the hole of the cathode is accurately centered, very intense beams of canal rays are available with diameters as low as one millimeter or so, because the biggest part of the discharge current arises from the close surrounding parts of the cathode.

The pressure inside the source is generally a few hundredths of mm Hg. Owing to the low diameter of the hole, very low gas consumptions and relatively low pumping speeds can be reached. The first source developed by these authors gave ion beam currents up to 1 ma, for 20 ma of discharge current. Power consumption was 1 to 3 kw, now considered a rather high figure.

There is a disagreement about the proton percentage available with that type of source in the case of hydrogen gas. According to Bouwers, Heyn and Kuntke (*3*) the beam consists mostly of molecular ions $H_2^+$. On the other side, Bothe and Gentner (*4*, *5*) stated that, in one case, they had obtained 25 $\mu$a of magnetically analyzed protons, which represented 65% of the total ion beam current. Other results indicate about 25 to 30% of protons.

**Source of Hailer**—Hailer (*6*, *7*) improved Oliphant and Rutherford's source by introducing an anodic plane screen facing the cathode, with a central hole 1 to 2 cm diameter to allow passage of the discharge.

Hailer states that this screen with the cathode plane acts as a pinhole electrostatic lens with very short focal length (a few millimeters) so that ions can be focused into the cathode hole. The hole itself is bordered with molybdenum, a metal with very high thermal conductivity.

The author compares the ionic output of his source with and without screen. With the optimal diameter (13 mm) the ionic current for hole diameter and length 1.3 and 1.7 mm, is almost twice the ionic current without screen, for hole diameter and length 3 and 5 mm. According to Knudsen's law, the gas flow is four times as great in the second case as in the first. So, the ratio (ionic current to gas flow) is increased in a proportion as high as eight to one by the screen.

Craggs (*8*), after a brief report on previous papers by Oliphant and Rutherford (*1*) and Hailer (*6*), describes experiments on canal-ray positive-ion sources of both types; we shall refer to one of them (of the second type) for some calculations.

With a voltage of 27.7 kv and 10 ma of main current, Craggs found an ion beam current 560 $\mu$a. The other parameters were as follows: gas pressure inside the chamber 0.21 mm Hg; canal diameter and length 1.5 and 2.1 mm; the anode screen aperture diameter was 13 mm as in Hailer's experiments.

According to Eq. 4, gas consumption was rather high (150 mg/hr); the weight of ions consumed was $1.17 \times 10^{-11}$ kg/sec so that the ratio was as low as 0.022%. This seems to be a good mean figure for that type of source. Craggs, after trying different devices, states that 35 kv is a technical upper limit of voltage for his type of source because of instability of the arc. However, an increase of this parameter seems desirable. Results with gases other than hydrogen are also given in this report.

**Source of Huber and Metzger**—Huber and Metzger (*9*) succeeded in maintaining stability up to 65 kv (current of 18 ma) by introducing a third auxiliary electrode brought out at a potential equal to half this value.

With canal diameter and length 2 and 3 mm, a 1200-$\mu$a current of hydrogen or deuterium ions was available. Let us assume a pressure 0.025 mm Hg (probable, but not certain) then, the flow of gas is about 30 mg/hr, and, tak-

ing into account the weight of the ions ($2.5 \times 10^{-11}$ kg/sec), we find a ratio of about 0.3%; i.e., ten times as great as the former.

Huber and Metzger measured their percentage of atomic ions and found values around 50%. That means that more than 500 $\mu$a of useful ions is the current available for acceleration.

**Other Such Sources**—Bjerge, Brostrom, Koch and Lauritsen (*10*) describe with some details a source of the Oliphant and Rutherford's type. Let us give a brief account of its performance: With 30 kv and 1 to 3 ma of main current they got 100 to 150 $\mu$a of target currents, which means output currents somewhat larger, through a canal of diameter 1.5 mm and length 7 mm, the inside pressure being $2 \times 10^{-2}$ mm Hg. We find that the ratio (weight of ions/weight of neutral gas) is at least 0.6% and probably twice that value. Attempts to improve the source by means of a screen as indicated by Hailer did not succeed.

The source of Bjerge *et al.* is interesting because, by means of three bellows, adjustment can be made of the position of: (1) the anode with respect to the cathode, (2) the cathode with respect to the upper part of the first lens, and (3) the upper part of this lens with respect to the lower one. Each adjustment can be commanded from the observation room (when the high voltage is on) by means of strings. Details are also given about the power supply and the acceleration tube.

Other sources of this type were used by Bouwers, Heyn and Kuntke (*3*), Bothe and Gentner (*4, 5*), Amaldi *et al.* (*11*) and others.

**Merits of High-Voltage Canal Sources**—These sources are among the most interesting described in the literature. They give ion beam currents up to several milliamperes, of which about 30 to 50% are atomic ions (in the case of hydrogen and deuterium). The gas consumption is rather high (from a few hundredths up to a few tenths of a gram per hour), which means weight ratios generally well below one percent. Power consumption is rather high (a few kilowatts) and power supply devices are expensive because of their high voltage.

On the other hand, the mean life of this type of source is comparatively long, because of the absence of filament (as we shall see, this is a great source of trouble in low-voltage sources).

Oliphant (*12*) states that high-voltage sources do not require as pure gases as the low-voltage ones. Craggs (*8*) adds that very small amounts of air or nitrogen result in a considerable lowering of the starting potential, without altering appreciably the proton content of the beam, which characteristic is not the case with other types of sources.

But in spite of some striking advantages, high-voltage sources are excluded from some applications where monokinetic ions are wanted. It is obvious that all the ions are not created in the same region of the arc and consequently undergo different accelerations before leaving the source. The mean square dispersion of energies is not so high as could be expected, about one fifth of the arc drop, but this dispersion is too high for measurements such as resonance levels for charged particles. Those measurements require Van de Graaff electrostatic generators for constancy of the main accelerating voltage.

### Low-Voltage Sources

Low-voltage canal-ray ion sources arise from some attempts to decrease electrical power consumption and to have monokinetic or nearly monokinetic ions.

**Source of Crane *et al.***—In 1934, Crane, Lauritsen and Soltan (*13*) maintained an arc of 0.5 ampere with a 1,000-volt drop in hydrogen at pres-



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sures as low as $10^{-2}$ to $10^{-3}$ mm Hg. They obtained a 200-$\mu$a ion current. Lamar and Luhr (*14*) used a low-voltage arc arising from a cathode in a box whose upper part formed the anode and whose lower part was negative with respect to the cathode. The ion beam was drawn through a gauze, a device which, they say, results in dissociation of molecular ions. With gas pressures from 0.3 to 0.4 mm Hg, they obtained a 500-$\mu$a current of hydrogen ions, with 98% of protons. Unfortunately, the gas flow of this source is exceedingly high, and necessitates very rapid pumping devices.

**Source of Fowler and Gibson**—Fowler and Gibson (*15*) described a source consisting of an arc chamber that contained a hot cathode and two anodes, which were connected to the opposite poles of a low-voltage transformer, whose central point was at cathode potential. The two anodes burn alternately. Beyond the cathode is an auxiliary electrode (somewhat similar to a probe) at a very negative potential (10,000 to 22,000 volts). Positive ions, coming from the plasma of the arc, strike the auxiliary electrode, and a few of them pass through a hole of 1-cm$^2$ cross section and 2.5-cm length.

The source is abundantly cooled, because power consumption is high: 3.5 kw or so.

Owing to the diameter of the hole, gas flow is very high. Pressure inside the arc chamber varies from 13 to 70 $\mu$ Hg; lower values give instability of the arc. The pressure outside the arc chamber is estimated to be one thousandth of these values.

Target currents of several milliamperes have been obtained; proton percentage is low at low pressures, but increases very rapidly with pressure. Many of the protons originate from broken molecular ions, a matter without importance for further uses. These values seem somewhat exaggerated, a fact probably resulting from insufficient protection against secondary electrons from the target, electrons which give, in turn, tertiaries when striking the walls, *etc.*

**Other Low-Voltage Sources**—Similar sources have been described by Tuve, Hafstad and Dahl (*16*) in a general paper on their high-voltage apparatus. With negative voltages at the extractor down to 4,000 volts, ten to thirty useful microamperes (a figure somewhat lower than the previous one) were available in the high-vacuum chamber. The pumping speed through the hole was not high: 3 to 10 cc per hour at normal pressure and temperature, which corresponds to 0.5 to 1.8 mg/hr for deuterium. High rates of atomic ions (55 to 90%) have been resolved magnetically. Seven types of sources, some of them including grids, are described by these workers.

Allen (*17*) describes another source that starts easily and delivers currents of protons and deuterons up to 25 microamperes. High rate of atomic ions needs good out-gassing of the source. This source operates at pressures as low as $5 \times 10^{-3}$ mm Hg, an interesting feature indeed. It is very steady.

**Merits of Low-Voltage Canal Sources**—Low-voltage hot-cathode canal-ray ion sources give low currents (about 20 microamperes) with a mean percentage of atomic ions about 50 (for hydrogen and deuterium). Increasing the total output (as in Fowler and Gibson) requires a considerable increase of the pumping speed.

The ratio of masses of ionized and neutral atoms passing through the hole is high only when the output is low; it reaches values of about 0.15%. Every attempt to increase the output results in a considerable lowering of that value. The total power consumption (arc plus filament plus extractor) is high, generally kilowatts.

The mean life of the cathodes is low because normal emission rates should give insufficient ionic densities. Since 1938, we have found no description of any source of this type in the literature.

## LOW-VOLTAGE CAPILLARY-ARC SOURCES

The fundamental object of the low-voltage capillary-arc ion source is to cause, by artificial means, a concentration of the low-voltage arc similar to that occurring naturally in the high-voltage low-pressure one.

**Source of Tuve *et al.***—In 1935, there appeared a complete description (*18, 19*) of a source that was considered remarkable for a long time. The principal features of Tuve, Dahl and Hafstad's source are as follows: the arc (0.2 to 2 amperes, generally 1 ampere) striking between a hot cathode (a 4 mm by 14 mm oxide coated strip of 2 mil platinum) and an anode is constricted through a cylinder (capillary) of 3.5 mm diameter and 18 mm length. The probe is at some distance from the axis, in a lateral clearance, and protected by a screen to prevent the arc from being blown out.

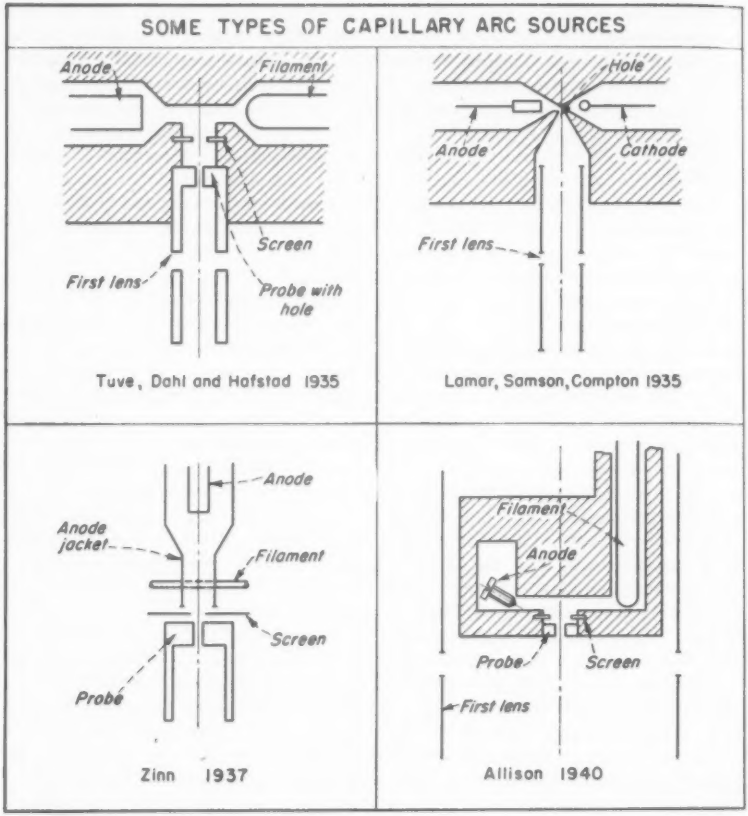
The hole is 1 mm in diameter by 4 mm in length. According to the probable value of the pressure ($3 \times 10^{-3}$ mm Hg), the gas consumption is therefore very low; we find theoretically 0.5 mg/hr, a figure confirmed by the authors' direct measurements that indicate about 10 cc per hour, i.e. 0.9 mg, taking into account the leaks in the whole apparatus. Power consumption is very low, only a few hundred watts.

According to the theory of probes by Langmuir and Mott-Smith (*20, 21, 22*) ionic current does not increase further when negative potentials beyond $-10$ or $-15$ volts are applied. However, Tuve *et al.* succeeded in increasing their probe currents as well as their target currents by applying potentials as low as $-6{,}000$ volts. This action probably takes place because the dimensions of the probe are far from negligible with respect to that of the arc. In such conditions, the development of the probe sheath toward the center of the arc, by increasing the negative voltage, allows more and more ions to be collected.

Target currents up to 1,600 microamperes have been obtained; the routine value seems to be around 500 microamperes. Comparing those values with that of the flow of gas, we find a ratio of masses of about 10%, a remarkably high value. Unfortunately, the proton content is exceedingly low. In a footnote, the authors give a precise result. It corresponds to 13.5% of protons, which is low compared to the previously described types of sources. The influence of gas pressure and of impurities seems to be very high. (We shall discuss this subject below.) The paper goes on to describe the focusing devices used with the source.

**Sources of Lamar *et al.***—These experimenters, working on sources of the capillary-arc type (*23, 24*), tried to avoid complications arising from probe voltage supply by drawing the ions directly by means of the high voltage of the accelerator. Attempts to increase proton ratio by introducing a breaking chamber at an intermediate pressure between that of the arc and the high voltage completely failed. Broken ions were found, but they did not originate from the breaking chamber.

Lamar, Buechner and Compton also designed an all Pyrex source on the same principle. The hole between the arc and the high vacuum was beveled in order to prevent burning under ionic bombardment. These types of sources need no cooling to give satisfactory performances. The all Pyrex source delivers 60 microamperes of hydrogen ions through a hole 0.5 mm diameter for arc current of 0.2 ampere




and gas pressure of $4 \times 10^{-2}$ mm Hg; about 20% are protons. The authors state that introducing water vapor considerably increases the proton content; values up to 80% were noted.

Another source of this type is described by Jorgen Koch in Danish (*25*).

**Source of Zinn**—Zinn described in 1937 another source (*26*) with low-voltage arc where the cylindrical capillary is replaced by a side clearance of 1 mm depth. The probe is facing the anode, and this orientation seems to result in an increase of the collected ionic current. As in Tuve, Dahl, and Hafstad's design, a screen prevents the arc from being blown out.

Ionic currents up to 4.3 ma have been obtained for arc currents from 0.5 to 2 amperes and probe potentials from −2,000 down to −10,000 volts. Focusing is difficult. Gas pressure is around $3 \times 10^{-2}$ mm Hg; gas consumption is around 1.5 mg/hr. Only 20% of the ion beam current is protons. Zinn states that filaments have very low mean lives (from 25 up to 50 hours). Slight modifications of some dimensions result in a considerable variation of the output current.

A further paper on the Zinn source has been published recently by Jorgensen (*27*). The features of Jorgensen's source do not differ essentially from those of Zinn's. The output current and gas consumption are both slightly lower, because the hole is different.

**Other Capillary Sources**—No other ion source presents so many varieties as the capillary arc one. From the numerous other descriptions, certain characteristic features are worth noting.

Getting, Fisk and Vogt (*28*) used, with their Van de Graaff electrostatic generator, an ion source very similar to Tuve, Dahl and Hafstad's, except that the capillary arc is curved. Gas pressure is high, from $10^{-2}$ to $10^{-1}$ mm Hg, and this results in an increase of the proton rate, probably because of a higher rate of collisions; 250 microamperes of hydrogen ions with 60% of protons are available. Introducing water vapor decreases the total output, but increases the ratio of protons.

Allison (*29*) recently published a very complete description of a capillary arc ion source. An abstract had been given previously (*30*). The principle differs only slightly from that of Tuve, Dahl and Hafstad's, but the construction is rather different. Cleaning and filament removal are very easy. Target currents of 15 microamperes of magnetically selected protons and 9 microamperes of magnetically selected helions have been recorded for 0.8 ampere arc current after acceleration through a 350 kv device. The gas consumption is about 4 mg/hr.

Other capillary arc sources have been described by Timoshenko (*31*), by Livingston, Holloway and Baker (*32*), and by others.

**General Features of Capillary Sources**—We have thus described those sources that present these important common features:

(1) The total ion output is high, up to several milliamperes.

(2) The proton rate is generally low, 15 to 25%.

(3) Focusing is generally difficult, and needs complicated lenses. (About 50% of the ions are lost between the source and the target in accelerating devices.)

(4) Power consumption is always low, a few hundred watts, but it is complicated because the source generally needs many sorts of different voltages for filament, anode, screen, probe, lenses, etc. (Lamar *et al.* avoid this complication, but their output is lower.)

(5) Gas consumption is always very low, the mass ratio of ion and neutral gas flows reaches values up to 10%.

(6) The capillary arc is generally very unstable and difficult to start. (Auxiliary arcs, generally striking between cathode and walls, are used to avoid these troubles.)

(7) The capillary arc sources are exceedingly sensitive to impurities. (The presence of oxygen, air, mercury, *etc.* in a hydrogen arc increases both stability of the arc and output ionic current, but according to Tuve *et al.* the hydrogen ion current decreases very much (*19*). Introducing water vapor seems generally to increase the proton content. It is known that, when an electrical discharge passes through a mixture of gases, the gas whose ionization potential is the lowest generally provides practically the whole passage of current, even if present in very small quantities.)

(8) The ions are practically monokinetic, within several volts. The source has so far been used for very precise energy-level measurements.

Comparisons between high-voltage canal-ray sources and low-voltage capillary-arc sources have been published by Oliphant (*12*), Roberts (*33*), Korsching (*34*) and others. The canal-ray source is simple, rugged, stable and easily used, but its power and gas consumption seem to be disadvantages.

The capillary-arc source is more complicated, sometimes capricious, but gives monokinetic ions. However, the recent development of oscillating-electron and high-frequency sources seems to outmode somewhat the capillary-arc ones, as will be seen below.

## FOCUSED ELECTRON-BEAM SOURCES

Since 1935, several authors have described sources in which ions are generated from the collision of an electron beam and an atomic jet. The beam and jet can be parallel or perpendicular with respect to each other, and to the direction in which the ions are withdrawn.

Focusing is generally obtained by a magnetic field. Because the electrons emitted by the filament generally have speeds corresponding to energies less less than 1 ev, they follow the lines of force very closely in a helicoidal motion, whose radius is of the order of one micron. In the first devices, each electron passed only once through the source. We shall refer to them as *flowing electron sources*. These sources seem to have been discarded because the ratio of the number of ions generated to the number of incident electrons was generally low. The usual practice now is to force the electrons to cross the atomic jet again and again; this is the principle of the *oscillating electron sources*. We shall also mention a source in which the principle of the focused electrons is combined with that of the arc. It is similar to those generally used now in cyclotrons.

### Flowing-Electron Sources

The first description of an ion source where a focused electronic beam intersects with an atomic jet was given in 1935 by Planiol (*35, 36, 37*). Both beam and jet are perpendicular to each other and to the direction in which the ions are withdrawn.

**Source of Planiol**—The cathode is a tungsten plane-spiral perpendicular to the direction of the electron beam; it is known that electrons emitted in any direction different from that of the magnetic field are immediately deflected back by it to the cathode. Five millimeters from the cathode is an accelerating grid whose potential is some hundred volts positive with respect to the cathode. The electrons collide with the atoms of the jet. The ions are drawn through an accelerating grid and directed toward the target by means of an electrostatic lens.

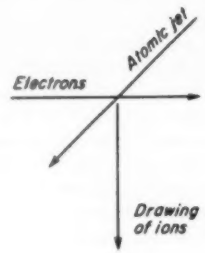
With 300 ma of electrons, target currents of cadmium ions as high as 600 microamperes were read, but secondary emission is probably high. According to Korsching (*34*), the true ion current hardly exceeds 80 microamperes.

Another source of this type was studied by Sampson and Bleakney (*38*). We may introduce for such a type of source another important ratio, that of the ionic beam to the electronic one. It is obviously low, less than one thousandth.

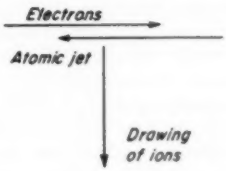
**Sources of Smith *et al.***—Smith and Carlock (*39*) in 1936 published a short paper on a universal ion source with a focused beam of electrons, whose principal features are very different from the previous ones. The focusing is provided by electrostatic means, one cylinder being the cathode itself. The beam strikes a jet of gas or an anode coated with the material to be ionized; the ions are, in turn focused by the electrostatic lens, go back in opposite direction to the electrons, pass through the cylindrical cathode, and into the utilization chamber.

This source was improved by Smith and Scott (*40, 41, 42*), who gave a very close theoretical analysis (*43*) that allows theoretical calculation of the minimum potential required for complete removal of the ions generated

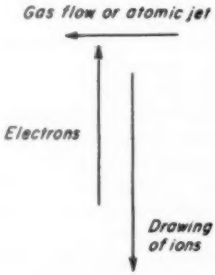
## ION SOURCES WITH FOCUSED ELECTRON BEAM



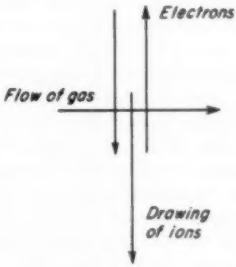

Planiol 1936



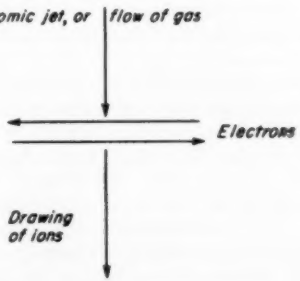

Sampson and Bleakney 1936




Smith and Carlock 1936




Finkelstein 1940




Von Ardenne, Heil 1942

in the source. This source operates at very low pressures (from $1 \times 10^{-5}$ up to $2 \times 10^{-4}$ mm Hg).

We make no attempt to summarize the theoretical paper. Concerning the experimental results, we should like to point out the following features. At $5 \times 10^{-5}$ mm Hg gas pressure, the measured gas consumption was 8 cc/hr at atmospheric pressure, i.e., less than 0.8 mg/hr in the case of hydrogen. For electronic beam current densities up to 2.2 amp/cm², total ion currents up to 1.5 ma have been measured. The ratio mass of ions to mass of gas is about 1%. That of ionic current to electronic current is 0.5%. Both may be considered very satisfactory values. Proton percentage varies from 5% to 80% of the total hydrogen ion current; this ratio depends upon electron energy and current density, but mainly upon pressure. It seems higher at very low pressures. The source last described was also tried with helium gas. The yield of helions seems to be of the order of 5% of the total current. (The different processes of ionization are pointed out in the theoretical paper, and general methods of increasing the rate of atomic ions are suggested.)

### Oscillating-Electron Sources

The ratios of mass of ions to mass of gas flow and ionic current to electronic current may be increased many times by forcing the electrons to pass again and again through the atomic jet with an oscillatory motion. Paths up to several meters are followed by the electrons before they strike the walls or electrodes.

**Source of Finkelstein**—Finkelstein first described in 1940 a remarkably high-efficiency ion source of the oscillating type (*44, 45*) in which oscillatory motion is parallel to the direction of drawing. The source consists of a cathode with a very high emission rate, and six plane perforated electrodes, three of which are at accelerating potential, and the three others, at retarding ones. The electrons are focused along the axis by means of Helmholtz's coils (a system which gives a very homogeneous magnetic field) to produce a field of a few hundred gauss. Thus, the electrons emitted by the cathode are first accelerated, and then stopped and sent back. But because they generally suffer some losses of energy by elastic collisions, they do not strike the cathode, and their motion becomes pseudoperiodic.

The only limitation to the length of their paths is that mutual repulsion results in a divergence of the beam, so that they end by striking the walls or the electrodes.

Somewhere in the beginning of the retarding region, the electron beam crosses a jet of gas arising from a capillary whose end is perpendicular to the axis of the source. Numerous ionizing collisions occur in that place; the ions are accelerated toward the utilization chamber and focused, first by the electron space charge and the magnetic field, and then by electrostatic means. Ions formed in the accelerating region of the source are lost.

The performance of Finkelstein's source is astonishing. Currents of hydrogen ions up to 150 milliamperes have been obtained for short periods, and 70 milliamperes seems a customary value. The ratio of ionic to electronic current is from 2 to 5%; that of ion mass to neutral gas mass is not calculable with precision, but seems to be not far from 100% for the maximum current. No other publication deals with such results.

Gas pressure outside of the jet is about $6 \times 10^{-4}$ mm Hg; below $2 \times 10^{-4}$ mm Hg, the beam is unsteady. Relatively large apertures suffice to maintain the pressure difference between the source and the high vacuum. Power consumption, taking into ac-

count that of the coils, is only a few hundred watts. The ions are monokinetic.

**Sources of Von Ardenne and of Heil**—These two German experimenters, working independently, developed ion sources which seem to be very similar to each other, and to differ from Finkelstein's mainly in that the oscillatory motion is perpendicular to the direction of drawing instead of parallel to it. This arrangement results in the possibility of having two cathodes emitting together or alternately, giving an increase of the electron flux or of the filament life.

In both sources, the electrons emitted by the filaments are accelerated toward an anode box (parallelepiped), whose interior is free of electric field. After crossing that box, they are repelled by the screen of the opposite cathode, etc. Somewhere in the field-free region they cross an atomic jet or a flow of gas. Magnetic guidance is provided by permanent magnets or electromagnets. The use of permanent magnets obviously reduces the power consumption. In both sources, the neutral atoms move parallel to the direction of the drawing.

With permanent magnets, Von Ardenne (*46*, *48*) obtains ionic currents up to 500 microamperes of hydrogen or deuterium ions, with about 50% of atomic ones. The power consumption is lower than in any other type of ion source. Gas consumption is 2 mg/hr.

Increasing the magnetic field by using electromagnets results in a considerable increase of the ionic current. According to Heil (*47*), the ratio (ionic current to electronic current) reaches, in the case of mercury, values as high as 75%. In the case of hydrogen, it is only a little lower.

**Atomic Jets**—The production of atomic jets for such sources is described by Planiol (*37*) and Heil (*47*). The material to be ionized is warmed in an oven, from which a small aperture, preferably not exceeding the mean free path at the oven's pressure, allows entrance to the ion gun. After crossing the gun, the atomic jet is condensed by a liquid air trap. This method is particularly suitable for materials like cadmium or mercury, which are liquid at normal temperature or have a low melting point.

In the case of permanent gases, the atomic jet is generally replaced by a gas flow arising from a capillary. However, Planiol suggests the possibility of extending the first method to almost all the permanent gases by the use of a liquid hydrogen trap, and to hydrogen itself by the use of a liquid helium trap. [See also a general study of the molecular beam technique by Estermann (*49*).]

**Advantages of Oscillating-Electron Sources**—We can summarize the properties of these sources as follows: (1) The ionic current can be rendered higher than in any other system of ion source. (2) The power consumption is lower than in other systems. (3) The ratios (ionic mass to atomic mass and ionic current to electronic current) can reach values in the neighborhood of 100%, but it seems that they cannot do so simultaneously. In Finkelstein's, the first ratio is high, the second, a few percent; in Heil's and Von Ardenne's, the second is high and the first lower. (4) The ions are monokinetic. Von Ardenne states that the dispersion of speeds in his source does not exceed 0.1 volt. (5) The life of filaments is several times longer than in capillary arcs. (6) The percentage of atomic ions in the case of hydrogen is about 50%.

It seems that oscillating electron sources are always preferable to capillary arc ones, because they are superior for each particular subject pointed out in this comparison. However, cathode life remains a problem. Some

experimenters think that oscillating-electron sources are preferable in all cases. Von Ardenne states that oscillating electron sources are especially adequate for pulse technique (for instance, neutron spectrography) because ions created during the intervals accumulate in the source so that very high instantaneous currents are available at the moment of the pulse.

Weisz and Westmeyer (*50*) described in 1939 a source which acts somewhat like Finkelstein's, but uses a true arc constricted by magnetic means. It is intermediate between low-voltage arcs and oscillating-electron arcs. The principle is very similar to that of cyclotron ion sources, which will be considered further on. The ions are drawn through an aperture of 2 mm diameter. The source requires high pressures (3 to 5 mm Hg). It seems less interesting than the previous ones.

## HIGH-FREQUENCY ION SOURCES

A new type of source that promises to give monokinetic beams and to have low power consumption and long life is the high-frequency ion source.

**Source of Thonemann**—A high-frequency discharge (*51*) is maintained in a spherical Pyrex vessel with outer electrodes excited with a five meters wavelength. The pressure is rather low, about $10^{-3}$ mm Hg. The power consumption is 200 watts. Ion currents up to 12 ma can be drawn by use of a potential difference of 20 kv.

According to Rutherglen and Cole (*52*), the proton ratio in the case of hydrogen is lower than 5%. However, this figure corresponds to 1 ma of pure protons, a rather high value in fact.

**Source of Rutherglen and Cole**—These authors describe (*52*) another source in which the proton ratio is increased up to 60% by using a magnetic field of some 100 gauss in the discharge space. The electron paths are focused along the axis of the discharge. Existence of a critical value for the magnetic field arises from the experiments. The ions are drawn through a hole of 3 mm diameter and 13 mm length. With a power input as low as 30 watts, ion currents up to 400 microamperes, with 240 microamperes of protons, have been recorded. Gas consumption is about 1.3 mg/hr for an inside pressure of 1.5 mm Hg.

The authors emphasize the fact that clean glass gives a higher percentage of protons than metallic walls. Blue discharges that are seen are always associated with low percentages, and red discharges, with high ones. It seems possible to increase the ion current up to very high rates by using higher power input and higher magnetic field.

**Merits of H-F Sources**—High-frequency ion sources are new devices undergoing extensive study at the present time, so that it is premature to conclude too much about them. But it seems that they give very satisfactory performances as a result of extremely low power consumptions, and presumably at lower pressures than any other source we have described. The main advantage should be, if suitably developed, the possibility of giving monokinetic ions without using a hot cathode, i.e. with lives at least as long as high-voltage heterokinetic ones.

## SOURCES FOR MASS SPECTROGRAPHS

Most of the previous sources are common to accelerating devices and mass spectrographs, so that there is little to add to what has been said.

**Arc Sources**—Arc sources have been used by many investigators for mass spectrograph studies. The main difficulty is not to build convenient sources, but to bring the element that is to be ionized into it in a suitable form. Very few elements are gaseous at normal or somewhat higher tempera-

tures. We make no attempt to summarize that very important and difficult question. See, for instance, Aston (*53*) or Thibaud *et al.* (*54*).

**Anodic Rays**—The ion beam current can be increased by use of incandescent anodes suitably coated. As early as 1906, Gehrcke and Reichenheim (*55*) had shown that the anode of an electrical discharge emitted positive ions (anodic rays) when it was coated with alkaline salts. Interesting sources are available by bombarding a coated electrode with an intense focused electron beam (*56*, *57*, *58*), or by using it as anode in an electrical discharge (*59*, *60*). In fact, the principle is similar to that of Kunsman's anode.

**Kunsman's Anode**—In 1925, Kunsman (*61*, *62*, *63*) discovered that alkaline coated incandescent metallic surfaces emit positive ions and stated that the emitted current obeys Richardson's law. Theoretical studies show that emission is only possible for elements whose ionization potential is inferior to the extracting potential of the support. Use of tungsten with adsorbed oxygen brings that limit up to 9 ev, and allows the process to be used for alkalines, metals of the aluminum group (Al, Ga, In, Tl) and some others such as Ru and Fe.

Kunsman's anodes have been studied and used as mass spectrograph ion sources by Smythe *et al.* (*64*), Koch (*65*, *66*), Walcher (*67*, *68*, *69*), and others. Emitted currents of 3 microamperes per square centimeter of anode have been noted for periods up to 35 hours.

**Ionization by Slow Electrons**—Very low intensity sources are available by bombarding the gas at low pressures ($10^{-5}$ to $10^{-6}$ mm Hg) with slow electrons (about 100 ev). The method was first used by Goldmann (*70*) and others [see for instance the review of Ritschl (*71*)] and mainly developed by Bleakney (*72*) and Blewett (*73*). That method has been improved by Planiol (*35*, *36*, *37*) and by Sampson and Bleakney (*38*) who used atomic jets and focused electrons.

**High-Frequency Sources**—Dempster (*74*, *75*) used another type of source with a high-frequency discharge (given by a Tesla coil) between metallic electrodes. The ions were withdrawn by means of a 20,000-volt extractor electrode.

## ION SOURCES FOR CYCLOTRONS

Cyclotrons need special ion sources because of their peculiar geometry and the presence in them of an intense magnetic field. There are two main types of applicable ion sources: (1) the filament source and (2) the low-voltage arc.

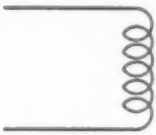
**Filament Sources**—The first cyclotron ion sources were filaments at as intense heats as possible placed along the central axis. Electrons emitted by the filament are accelerated by the dees and describe cycloidal, or up and down, paths in the magnetic field. Rather complicated paths of several meters length are sometimes attainable and the probability of ionization is acceptable in spite of low pressure. The electrons are collected by an anticathode.

By such methods, Lawrence and Livingston (*76*, *77*) and others obtained 1–10 $\mu$a ion currents. It must be noted that, because of synchronization of the radio-frequency power and the magnetic field, that figure represents almost the true rate of desired ions; the remaining ions are generally not accelerated, except when the ratio of charge to mass is the same.

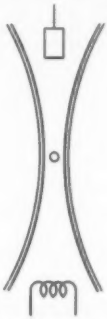
Increasing the heating power of the filament results in an increase of the electronic emission; hence, of the number of generated ions. With 1,000 watts, several investigators (*78*, *79*) obtained 100 $\mu$a of target current.

**Arc Sources**—The ion currents given by filament sources are not very

## EVOLUTION OF ION SOURCES FOR CYCLOTRON, SINCE 1931

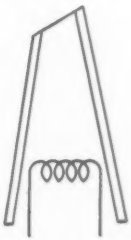


Filament source 1931



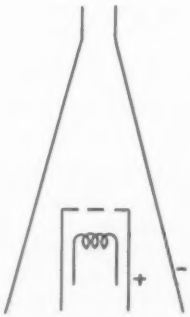
Conventional capillary arc 1939

Capillary arc with central slit 1944



Capillary arc with removed anode jacket 1939

Hooded arc 1945




Baumgartner et al. 1942

intense even for very powerful filaments. Some investigators tried to provide cyclotrons with more or less conventional ion sources.

Livingston, Holloway and Baker (*32*) used a low-voltage capillary arc similar to that of Tuve, Dahl and Hafstad. Their calculations showed that very few of the ions entering the high-vacuum chamber would be sent back to the walls of the source by the magnetic field. With an electrical power consumption of only 300 watts, they got target currents up to 480 microamperes; i.e. the ratio (ionic current/power consumption) was increased by 16 to 1.

During the following years, improvements in the pumping speed allowed greater and greater apertures between the arc chamber and the high vacuum. Livingston (*80*), using ultra high-speed pumping devices, succeeded in extracting the ions all around the arc by means of a circular slit between two (anode and cathode) conical jackets.

But it must be noted here that the presence of an intense magnetic field parallel to its axis results in special properties of the arc. The electrons emitted by the filament as well as their secondaries are focused (as has been described previously). Thus, the arc is magnetically constricted, and the electrons move forward and backward along the lines of force. But their space charge results in divergence toward the outer part. So we may maintain a discharge between the cathode and the cathodic jacket, and remove both the anode and the anodic jacket.

McMillan and Salisbury (*81*) and Alkhazov *et al.* (*82*) described sources of this type. Visual observation shows that the plasma of the arc extends very far out of the cathode jacket onto the high vacuum chamber. Because the hole is very large, (several millimeters in diameter), very high pumping speed is necessary. An important fraction of the ionization occurs directly in the high-vacuum chamber; thus, it may be stated that the source actually acts more as an electron source. Focusing of the ions is provided by means of "feelers," connected to one of the dees.

**Hooded Arc**—For easy focusing in the cyclotron, it is desirable to limit the extent of the arc outside of the cathode jacket. It is obvious, indeed, that the ions generated too far from the plane of symmetry have a great probability of striking the dees; their kinetic energy becomes heat, resulting in many troubles: increasing the radio-frequency power consumption, heating and perhaps melting the dees, etc.

In the hooded arc (*83*, *84*) limitation is provided by mechanical means; the hood is an extension of the cathode jacket. With 100- to 150-volts arc drop, and 2- to 3-amperes main current, output ion currents up to 100 milliamperes are available, with about 10% of it atomic. Unfortunately, the losses by lack of focusing are very high.

Pressure inside the arc chamber averages $10^{-2}$ mm Hg; pressure outside is $10^{-5}$ mm Hg. Owing to the dimensions of the hole, pumping speed reaches 5,000 liters per sec. Livingston (*84*) states that filament lives of 50 to 100 hours have been obtained.

**Oscillating-Electron Source**—The principle of oscillating electrons is obviously very suitable for cyclotrons because the magnetic field is automatically provided. Baumgartner *et al.* (*85*) in Zurich used a source whose principle is similar to that of Finkelstein's. The electrons are first accelerated by a positive grid, and then braked and sent back by the jacket, which is here negative, resulting in an oscillatory motion. Focusing is provided by the main magnetic field. It is useful to disturb somewhat the lines of force by means of a piece of iron, in order to focus the ions into the exit hole. By use of a suitable cylinder, a beam of 2 $cm^2$ cross section can be focused in

such a manner. Accelerating 50 ma under 250 volts, the authors recorded output ionic currents up to 1 ma. Percentage of atomic ions has not been measured.

## OTHER SOURCES

**Source of Franzini**—Let us mention briefly a very special ion source, that of Franzini (*86*). It is known that palladium is frequently used for purification of hydrogen. By heating a cylinder of that metal, a very tiny flow of gas (which depends on temperature) passes through it. The method may be used for regulating the gas flow in an ion source; control of temperature provides control of the pressure outside the cylinder.

Franzini used that principle for generating ions directly in the high vacuum, by maintaining a high difference of potential (20 kv) between the palladium tube and a negative electrode surrounding it. Ion currents up to 300 microamperes are available in this way. The pressure inside the cylinder is the atmospheric one.

With this special device, we end our survey of ion sources. Further information on older sources is in a complete review of Ritschl (*71*) (107 references of which about 50 are descriptions of ion sources).

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## Editor's Note

RADIOACTIVE PHOSPHORUS has been used by B. Selverstone, A. K. Solomon, and W. H. Sweet, to locate brain tumors. This work is reported in the *Journal of the American Medical Association*, May 21, 1949, for a preliminary group of 14 cases in which the Geiger-Müller counter was employed at the operation. In 11 of the 14 cases the counter was used to determine the precise location of tumors which did not show on the surface. Patients had received from 0.95 to 4.2 millicuries of radioactive phosphorus prior to the operation. Miniature counters were constructed by Charles V. Robinson of the Harvard Medical School. Counter diameter finally adopted was 3.0 mm. The counting rate close to the tumor increased from 5.4 to 36.3 times that encountered in the controlled area.

This report emphasizes again a statement made by W. Walter Wasson in the *Journal of the American Medical Association*, May 14, 1949, that 100 percent accuracy in diagnosis and treatment of malignant diseases is almost absolutely necessary. Instrumentation for these specialized needs clearly requires the careful application of the best available techniques.

As Wasson states in his Chairman's address before the Section on Radiology, American Medical Association, there is an unexplained wide variety of radiation (from 140–1,000 kv) used for the treatment of similar tumors in similar cases. Wasson pays tribute to pioneers in the field of radiology, but suggests detailed studies of tissue cell reaction must be extended.

# NEUTRON WELL LOGGING

**Largely neglected by the petroleum industry only a few years ago, neutron curves are now run almost everytime a radioactivity well log is made. The neutron method combines valuably with gamma-ray well logging discussed previously**

By ROBERT E. FEARON

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NEUTRON WELL LOGGING is a geophysical method of logging a boring in the earth by scanning the exposed strata successively with a detector of ionizing radiation and a source of neutrons, fixed with respect to one another, but moving as a unit in the borehole. The logging curve derived is a report of the intensity of the secondary ionizing radiation, plotted versus depth, for every depth in the boring.

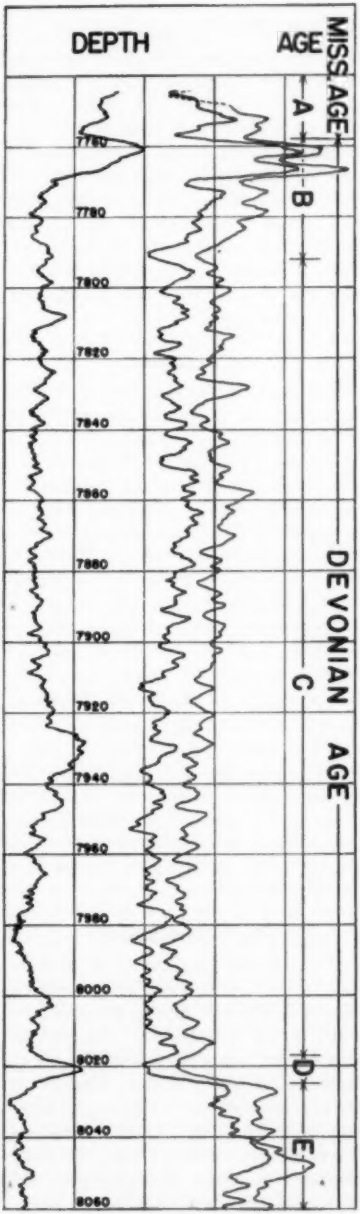
The circumstances are so chosen that the gamma rays contributed by the radioelements inherent to the strata (*1*) represent only a negligible part of the intensity observed. The radiations thus caused, each of which forms a part of the measurement reported on the neutron logging curve, have the following possible origins:

- **A.** Radiative transitions from excited energy states of nuclei energized by inelastic collision with fast neutrons (fast neutron excitation).
- **B.** Capture radiation caused by neutrons which have lost their kinetic energy in the mass of rock (slow neutron excitation).
- **C.** Fission.
- **D.** Radioactivity (subsequent emission of gamma rays) of materials capable of being excited in the period of exposure corresponding with the passage of the instrument.

Any or all of these processes may occur simultaneously in the rock. They are influenced in every case by the molar concentrations of all the isotopes of all the elements present, and could be calculated from the products of these molar concentrations by the cross sections for these processes for any given spectrum of neutrons. Such a calculation could be made if:

1. we knew all these molar concentrations
2. we had available the required cross sections for all energies of neutrons, and
3. we knew the energy spectrum of the neutrons throughout the matter surrounding the source.

Complete chemical analyses and data on isotope abundance would be sufficient, in principle, to specify the nuclear properties of a mass of rock. However, a chemical analysis would need to be especially complete and include even rare elements since some of these may interact strongly with neutrons, or release very energetic gamma rays, or both. Such analyses are very costly, and are practically never available in any number on systems of rock samples obtained from wells. Furthermore, it is so difficult to separate many common elements from silicate complexes thoroughly that, even for these, the available analyses of rock




**Plots of gamma-ray (left) and duplicated neutron curves (right) for a well in TXL Field, Ector County, Texas. The gamma-ray curve is used to point out zones (A and D) of fine sediment, the neutron curve to recognize fluid (hydrogen content) in the other rocks (B and C). Whereas coring gives no accurate data on oil-filled Devonian chert (zone C), which has commercial quantities of petroleum in heterogeneous fine fractures, it is satisfactorily sampled by the neutron curve. Top of zone B is a hybrid rock-type, shale (radioactive) and limestone (maximum on the neutron curve) mixed.** *(Courtesy of Lane-Wells Co., Los Angeles)*

strata are often very much in doubt. For the rarer and less studied elements, the less said, the better.

Our second "if" is tantamount to a requirement that we have in our possession thoroughly accurate data of the kind needed to make an elegant approach to the design of nuclear fission bombs. It goes without saying that those working in industry do not have the opportunity to possess such information.

Our third "if" requires a knowledge of the first and second for its elucidation, since we must know what nuclei are present and how they remove energy from the neutrons initially emitted. Without this we cannot tell what the energy spectrum of the neutrons may be throughout the mass of matter which surrounds the source. We have tacitly assumed that the nature of the source is thoroughly determinable, something which may or may not be so in any given case.

Because it is so complex in its physical nature, and because of lack of opportunity to perform completely valid and thorough control experiments, the practical knowledge of neutron well logging is derived from a vast array of more imperfect practical experiments in the laboratory and in the field. The necessity for such relatively unsatisfactory methods of scientific research

has led to a superficial resemblance between the applied studies connected with neutron logging, and the more qualitative phases of botany and zoology. This resemblance is only superficial, nonetheless, since there does exist a framework of physical theory well capable of accurately integrating the subject. Numerous flaws and shortcomings which exist in the framework of physical theory of neutron logging are constantly under attack and are growing rapidly fewer.

### Apparatus

The neutron source shown in Fig. 1 is surrounded by a gamma-ray shield to emphasize the relative influence of the neutrons emitted by the source (*2*). The other features of the apparatus essential to neutron well logging are of a nature requisite to accomplish the measurements described in the referenced patents (*3*, *4*) and to eliminate, or minimize, the various spurious effects which interfere with the measurements of processes caused by neutrons. Among other things, there is an amplifier generally similar to one described for use in measuring ionizing radiation in a well bore (*5*, *6*), and an ionization chamber like that illustrated in another neutron logging patent (*7*). A fuller discussion of the need to influence the distribution and nature of the source radiations by shielding is found also in the patent (*8*).

### The Neutron Source

For the most part, practical capsuled sources which might be considered adaptable for well logging produce very small fluxes of neutrons. This is the case for mixtures of powerful gamma rayers with heavy water, because of the low cross section of the $(\gamma,n)$ reaction of deuterium. Also, the use of boron in the presence of an alpha-ray emitter yields poor fluxes for practical quantities of alpha-emitting radioelements. Of the easily available reactions, the $(\alpha,n)$ reaction of beryllium has by far the best flux for a capsuled source.

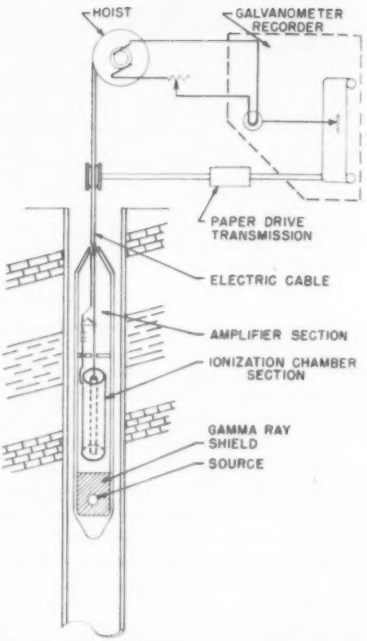



**FIG. 1. Essential components of an apparatus for performing neutron well logging in a cased or uncased boring in the earth. A means, not shown, permits casing collars to be observed independently of the radiation measurement as the logging instrument passes them. With such observations, logs can be easily and accurately related to any desired datum plane for depth measurement**

The use of high voltage tubes for generating X-rays or gamma rays was considered by Bender (*9*). In well-logging equipment, the insertion of various neutron generators using accelerated particles lies in the same category as Bender's suggestion. Space limitations in a practical instrument for nuclear well logging impose very severe design difficulties on anyone seeking to adapt ordinary accelerator-type neutron

generators to well logging. Because of such obstacles, attention here is directed toward the capsuled sources, and particularly to those utilizing the reaction of alpha rays upon beryllium.

Bernardini (*10*) shows the inception of neutron generation in $Be^9$ by alpha rays at a standard air range of 12 mm, corresponding to a bombarding energy of about 2.3 Mev. Thus most of the common alpha rayers will cause a yield of neutrons from beryllium, although greater total fluxes are secured when more energetic bombardment is employed.

A mass balance (*11*) of the $(\alpha,n)$ reaction on $Be^9$ shows that energy of 5.58 Mev is available in the reaction from this source. The energy which could, at maximum, be liberated into the neutron, after being shared with the $C^{12}$ nucleus, comes out, for polonium alpha rays, at about 10.1 Mev. This quantity is perhaps 0.2 Mev less than the maximum observed (*12*). To account for this discrepancy, one can readily assume that there is a sufficient net error in the mass values used. Furthermore, the apparently continuous energy distribution of neutrons can readily be reconciled with lines (*13*) of the accompanying gamma-ray spectrum if one recalls that the Po-Be source used by Richards (*12*) represented a thick target condition (beryllium exposed to polonium alpha rays).

Therefore, taking the radium-beryllium mixture as illustrative of the properties of a capsuled neutron source, we can set down the following list of properties of such a source of neutrons:

It emits—

A. the gamma rays of the radium series

B. a group of powerfully penetrating (in light elements) hard gamma rays of disintegration, many of which will exceed 5 Mev per quantum

C. neutrons having an energy distribution extending to a maximum value of about 12.4 Mev and ranging downward through a wide distribution to zero.

There will be, in addition, a very few 13.5 Mev neutrons due to the 9.0 Mev alpha group of radium C′ and even rarer ones due to the other members of the long-range spectrum of radium C′. Since, however, all these extra-energy neutrons total less than one twenty-thousandth of those caused by the main group of radium C′ alone, and bulk even smaller in the total picture of the aged capsuled Ra-Be source, they shall be neglected in the considerations to follow.

### Secular Equilibrium

For the most energetic neutrons issuing from a capsuled source, surrounded by rock adjacent to a borehole, the population achieves its constant equilibrium value a very short time after the source is introduced. This time is so short that it has no consequence whatever as a disturbing factor in neutron well logging, where the scanning speeds are, at most, a few thousand feet per hour.

The substantially constant number of particles of the neutrons of maximum energy may be likened to the atoms of a long-lived parent radioelement. Unlike the parent radioelement which has only one or two decay products, the neutron has an infinite number of daughter groups of neutrons of lower energy. For each such daughter group, there is an equilibrium value for the number which will be sustained by the parent. This value is determined by the ratio of the partial decay constant of the parent into the given daughter to the total decay constant of the daughter. (The equilibrium population of neutrons of maximum energy is the ratio of their rate of production in the source to the total "decay constant" for this energy group. The

"decay constant" is exactly analogous to the probability factor of the same name as it is employed in the theory of radioactive disintegration, and is greater for the maximum energy neutrons, where there is a high probability per unit time that these neutrons will leave their energy group because of energy losses in the rock.)

The final solution to an equilibrium population can be approached by a sequence of formulations in which successive approximations (up to the number which corresponds to the order of approximation) of the sums of the neutron intensities at each chosen energy are considered. These intensities are contributed by the total of the first degradation processes which produce neutrons of the chosen energy. Such a sequence of approximations converges much more rapidly for values of the equilibrium neutron population having energies close to $E_{max}$, and more slowly for those values corresponding to lower energies.

Thus, values of populations of neutrons of all energy groups, in equilibrium with a monochromatic source may be, in a first approximation:

$$ {}_1n_{E_0} = \left(\frac{N_{max}}{\lambda^t_{E_{max}}}\right)\left(\frac{\lambda^{E_0}_{E_{max}}}{\lambda^t_{E_0}}\right) \qquad (1) $$

where $N_{max}$ represents the number of neutrons of maximum energy originating per unit time from the source,

$\lambda^t_{E_{max}}$ expresses the limit of $p/\Delta t$ as $\Delta t$ approaches zero, in which $p$ is the probability of a neutron of energy $E_{max}$ being degraded in the rock during interval of time $\Delta t$,

$\lambda^t_{E_0}$ expresses the limit of $p/\Delta t$ as $\Delta t$ approaches zero, in which $p$ is the probability of a neutron of energy $E_0$ being degraded in the rock during interval of time $\Delta t$,

$\lambda^{E_0}_{E_{max}}$ expresses the limit of $p/\Delta t$ as $\Delta t$ approaches zero, in which $p$ is the probability of a neutron of energy $E_{max}$ being degraded in the rock into a neutron of energy $E_0$ in the rock during the interval of time $\Delta t$,

${}_1n_{E_0}$ designates the first approximation of the equilibrium population of neutrons of energy $E_0$ produced in the rock by neutrons of energy $E_{max}$.

To give these energy groups a finite meaning, the population groups spoken of must be understood to be population densities per unit energy interval.

The first approximation above is rendered inaccurate by the fact that daughters of the parent neutron radiation of maximum energy exist between $E_{max}$ and the energy $E_0$. These daughters, in turn, may be degraded into neutrons of energy $E_0$, which swell the total of those in the latter group.

A solution may be approached by perturbations, proceeding to account first for daughters of daughters, as follows:

$$ {}_1n_{E_0} = {}_1n_{E_0} + \int_{E_0}^{E_{max}} \left[ {}_1n_E \lambda^{E_0}_E / \lambda^t_{E_0} \right] dE \qquad (2) $$

where ${}_1n_E$ is the first approximation (see Eq. 1) of the population per unit energy interval for neutrons having energy $E$,

$\lambda^t_{E_0}$ is as defined for Eq. 1,

$\lambda^{E_0}_E$ expresses the limit of $p/\Delta t$ where $p$ is the probability that a neutron of energy $E$ will be degraded in the rock into a neutron of energy $E_0$ during interval of time $\Delta t$.

Obviously, for neutrons of energy $E_{max}$, ${}_1n_E$ and all subsequent approximations must always equal $N_{max}/\lambda^t_{E_{max}}$.

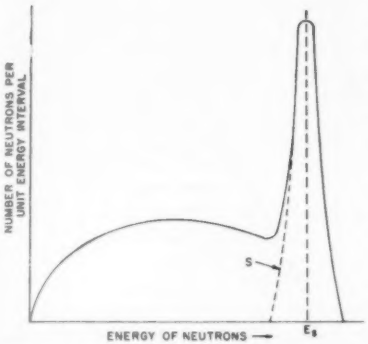



**FIG. 2. Distribution of secondary neutrons of lower energy in a rock caused by a primary source emitting neutrons with energy $E_0$. The dotted portion of the curve, S, is the lower end of the unaltered distribution emitted by the source as it would be observed if no neutrons suffered energy losses**

If the source of neutrons of energy $E_{max}$ is strictly monoenergetic, then the integrand of the right-hand member of Eq. 2 is infinite for $E = E_{max}$. In performing the integration, the author has assumed that this point was ignored. The term ${}_1n_{E_0}$ represents the portion of the equilibrium population of neutrons of energy $E_0$ caused by degradation of neutrons of energy $E_{max}$ into the $E_0$ group.

From the first to the $Z$th approximation of the value of $n_{E_0}$, the quantity $\lambda^t_{E_0}$ is a constant, dependent on $E_0$ and nuclear properties of the rock only. The quantity $\lambda^E_{E_0}$ is a function of $E$ determined by the nature of the rock in which the neutrons are introduced. Therefore, the procedure is:

$$ {}_{Z+1}n_{E_0} = {}_1n_{E_0} + (\lambda^t_{E_0})^{-1} \int_{E_0}^{E_{max}} {}_Zn_E \lambda^E_{E_0} dE \quad (3) $$

This process will converge rapidly, in general, because of the steadily decreasing population significance as we proceed from daughter to daughter, *etc.* The symbols here are the same as were used in Eqs. 1 and 2. As in Eq. 2, the infinite point of the integrand at $E = E_{max}$ is to be ignored.

The preceding series of perturbations resembles very closely the time sequence of events which transpires as equilibrium is being established.

Distributions of energy resulting from a homogeneous source of neutrons may thus be computed if we know the quantity $\lambda^{E_2}_{E_1}$ for all values of $E_2$ and $E_1$ for the infinite rock environment in which the source is placed. There will, therefore, be, for every rate of introduction of neutrons of a given energy from a neutron source, a function representing the neutron population at every smaller energy caused by the given flux of primary neutrons. Figure 2 illustrates this idea diagrammatically.*

If the source emits a distribution of energies, we can superimpose the functions due to each energy group in the source, additively, and thus arrive at the equilibrium energy distribution caused by such a source in the rock.

Thus, what is needed for the description of neutron population in the rock is an empirically derivable nuclear function of the rock, if there is an adequate description of the source. For every rock, the $\lambda^{E_2}_{E_1}$ is a surface that rises from a zero value in the plane $E_1,E_2$ along the line $E_1 = E_2$ and vanishes absolutely, except in very rare cases, over all of the plane where $E_1 > E_2$. There will also be, in this surface, a diagonal ridge running roughly parallel to $E_1 = E_2$ on the side $E_1 < E_2$. The surface will have lower values but, in general, will not vanish anywhere in the region having boundaries at $E_1 = 0$, and the line $E_1 = E_2$, and extending indefinitely in the direction of increasing $E_2$. Figure 3 illustrates such a surface. It shows the kind of surface that might be expected for a typical dry rock as

* Because it was not possible to show a truly homogeneous source on the coordinates in Fig. 2, the author has represented a monochromatic source by the nearly equivalent distribution shown.

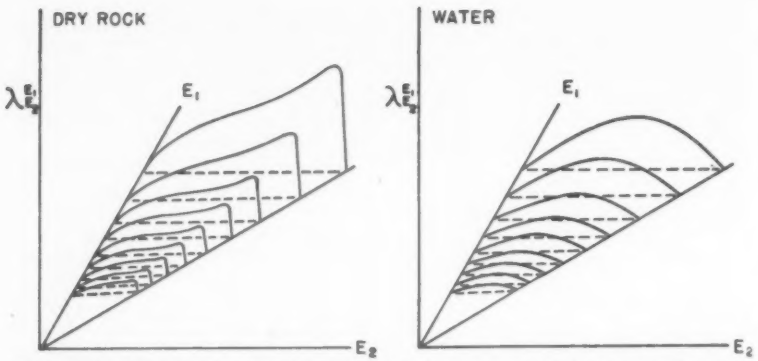



**FIG. 3. Surfaces representing the probability that neutrons having energy $E_2$ will be degraded to a lower energy $E_1$. In the successive sections parallel to the $E_2, \lambda_{E_2}^{E_1}$ plane, maxima fall farther left in the surface representing water because of abundance of hydrogen in water which brings about high probabilities of large energy losses**

compared with one for a mass of water or oil, in which the most probable energy losses are larger.

The $\lambda_{E_2}^{E_1}$ surfaces are mathematically difficult to develop from experiments based on thick rock masses. On the other hand, such data are experimentally difficult to develop from thin sections, unless very strong homogeneous neutron fluxes are available. Consequently, these large difficulties have held back this line of investigation. On the other hand, the empirical determination of such surfaces for representative rocks offers the best hope of achieving an elegant approach to the evaluation of neutron populations.

In deriving these total energy distribution statistics applying to the entire history of all the neutrons, no assumptions were needed regarding the distribution of sources in space. These methods will, therefore, hold for all source arrangements, whether point, plane, cylindrical, or otherwise.

### Space Distribution of Radiations

Since even the empirical nuclear properties of rocks are rarely known in the manner just presented, it is necessary to proceed to other desired conclusions by cruder methods of reasoning or by hypotheses which seem reasonable or are based on geophysical experience.

We have so far, considered only the question of energy distribution of neutrons and ignored entirely the question of their space distributions. By resorting to very simple hypotheses on the laws of energy loss for neutrons, Wallace (*14*) has shown how the space distribution of the thermal-energy group varies around a point source of fast neutrons in an infinite medium. The pile-design problem, for which Wallace's treatise is intended, has many points in common with the neutron well-logging theory. It is difficult to determine whether Wallace's assumptions permit the direct application of his general theory to well problems, or whether, on the other hand, a more refined theory is needed to explain the phenomena of well logging. Thus far the question is relatively unimportant because lack of sufficient general nuclear data on rocks does not permit a careful application of any elegant theory, however good.

We proceed, therefore, to write down an empirical formula for the intensity of gamma rays present in a cavity in rock, at a distance $r$ from a point source

of neutrons:

$$r^2 I = SQCe^{-\mu r} \quad (4)$$

where $I$ = intensity of gamma rays, in terms of radiant energy per unit time per unit mass, absorbed by a small quantity of inert matter placed in the cavity

$S$ = source strength

$Q$ = a factor due to the neutron spectrum of the source

$C$ = a "chemical factor," corresponding to the average effectiveness with which elements present in the rock convert the neutron flux into a gamma-ray flux

$\mu$ = the value to which the full absorption coefficient for the neutron flux converges as more and more rock is penetrated by the radiation

$r$ = the distance through rock to the cavity from the source of neutrons.

It will be noted that Wallace's general equation (*14*) for slow neutron density in the neighborhood of a point source of fast neutrons converges to the same form for $r$ large. With reference to interaction of neutrons in paraffin, it is interesting to compare also the related experimental data of Dunning, Pegram, Fink, and Mitchell (*15*).

The fact that maximum energy neutrons should suffer exponential attenuation is self-evident, but it is indeed a simplifying circumstance that the population density of derived slow neutrons falls off with distance according to the same attenuation law at large distances.

For a well bore full of water or petroleum, and for a well whose diameter is small compared with the distance between source of neutrons and gamma ray detector, the above reasoning seems to apply very well. For other cases, the consideration is too complex to admit of treatment within the scope of this article.

The significance of the variables in Eq. 4 is, for the special case above described, as follows:

$S$ is a constant, characteristic, for example, of the amount of alpha-emitting substance mixed with beryllim in the source capsule.

$Q$ is a quantity which increases as the energy of the most energetic populous group of neutrons present in the source flux becomes larger.

$C$ is a quantity which is not subject to large variations, but tends to be larger for dry rocks than for wet ones (because, for example, gamma rays resulting from capture are more energetic for most other earth elements than they are for hydrogen).

$\mu$ is the determinative quantity, and is critically influenced by the hydrogen content of the rock; $\mu$ becomes greater when the molar concentration of hydrogen increases.

Effects due to influence of hydrogen on C and $\mu$ cooperate to decrease the intensity of the radiation for increasing hydrogen concentration. It is for such reasons that the neutron curve is a convenient method of studying variations of hydrogen content in the strata. The relationship of the neutron curve to hydrogen content is, in certain cases, sufficiently exact to permit a quantitative calibration in a given well in terms of percent of petroleum-filled (or water-filled) pore spaces (*16*). Studies are being undertaken to enable accurate comparisons to be made from well to well wherever there is sufficient lithologic similarity.

### Importance of Several Nuclear Processes in Neutron Well Logging

It will be recalled that the processes for generation of gamma rays due to dissipation of neutron flux resulting from a fast neutron source were listed as follows: Excitation (fast neutron); Capture (slow neutron); Fission; Induced Radioactivity (delayed effects).

**Ten Most Abundant Elements in the Earth's Crust**

| *Element* | *General abundance in earth's crust (percent)* | *Isotope mass number* | *Gamma ray of capture (Mev)* | *Percent present in naturally occurring isotope mixtures* |
|---|---|---|---|---|
| Oxygen (O) | 46.710 | 16 | 4.1 ± 0.06 | 99.76 |
| | | 17 | 8.0 ± 0.2 | .04 |
| Silicon (Si) | 27.690 | 28 | 9.3 ± 0.8 | 89.6 |
| | | 29 | 10.6 ± 0.7 | 6.2 |
| | | 30 | 5.9 ± ? | 4.2 |
| Aluminum (Al) | 8.070 | 27 | 8.0 ± 0.5 | 100 |
| Iron (Fe) | 5.050 | 56 | 7.8 ± 0.7† | 91.6 |
| Calcium (Ca) | 3.650 | — | 7* | Mixed isotopes |
| Sodium (Na) | 2.750 | 23 | 7.1 ± 0.4 | 100 |
| Potassium (K) | 2.580 | 39 | 7.2 ± 0.4† | ~100 |
| Magnesium (Mg) | 2.080 | 24 | 6.8 ± 0.6 | 77.4 |
| | | 25 | 12.1 ± 0.5 | 11.5 |
| | | 26 | 6.0 ± 0.6 | 11.1 |
| Titanium (Ti) | 0.620 | — | 8* ± 2 | Mixed isotopes |
| Hydrogen (H) | 0.140 | 1 | 2.35 ± 0.01 | 99.98 |

* Estimated theoretically.
† Experimental data reported by Kubitschek and Dancoff at the April, 1949, meeting of the American Physical Society (not yet in print). All other data based on published mass defects.

Of these processes, excitation and capture can readily be shown to be the most important in a typical sedimentary rock. Feld (*17*) and others who have considered the problem of excited states caused by neutrons have shown that, in general, these states are spaced apart by about 0.8 Mev for light elements. Therefore, gamma rays generated in the sediments by decay of excited states usually lack the energy required to give them a strong emphasis if measured in a cavity in the rock. How the quantum energy of a radiation (observed by an ionization chamber placed in a cavity) contributes weight to the relative effect due to that radiation has been previously discussed (*1*). Competing with excitation, also, is elastic dissipation of the neutron's energy, which will generally preponderate, for the common elements of the earth.

Capture, on the other hand, is a process which will occur eventually to every neutron. The binding energies of neutrons in the light elements will set the limit for the size of the energy quanta that will be emitted when capture occurs. These energies are typically quite large, generally larger for other elements than for hydrogen. This is shown on this page in the table which also gives general abundances for the ten elements that make up 99.34% of the earth's crust (*18*).

The neutrons will generally be captured at thermal energy in all rock masses where the average nuclear cross section for non-capture energy losses remains very large compared to the average cross section for capture down to thermal energies. This is usually true for the typical limestones, sandstones, and shales, which compose the bulk of the sediments. Therefore the values given in the table can generally be considered to represent the energy released by a neutron uniting with any of the listed nuclei.

The "chemical factor" given in Eq. 4 may accordingly be evaluated by taking the weighted average of the capturing nuclei present in the rock. The weighting factor for each element

present will be its molar concentration in the rock multiplied by its capture cross section (*15*) for thermal neutrons multiplied by a factor depending on the energy emitted per capture process for the given element and on the gamma energy spectrum that corresponds with such emission.

### Sampling in Neutron Well Logging

In neutron well logging, as in gamma-ray well logging, the sampling process differs from that prevailing in coring. The weighting factor for the observed matter near the instrument falls off with distance from the instrument in both the neutron and gamma-ray methods. However, the manner in which the weighting factor varies throughout space is radically different in the two cases, making it a matter of particular interest in neutron well logging to consider the shape and size of the sample observed.

As before, for convenience, we define our sample as the mass of matter within an iso-weighting factor surface for the measurement. There is no unique meaning to the term "weighting factor," unless we define, in addition, the quantities to be observed in the sample and adopt an arbitrary rule for choosing the weighting factor to be observed on the surface which will contain the sample:

**A.** The weighting factor in neutron well logging is the rate of change in detected secondary radiation intensity with respect to molar density of the representative substance at the point for which the weighting factor is determined. (The term "secondary radiations" is a reference to gamma rays caused by neutrons derived from the neutron source.)

**B.** The relative weighting factor is the ratio of the weighting factor at any given place to the value it would have at its minimum between source and detector, on a line joining them, if the space between source and detector were filled with material of the same nature as the surrounding rock.

**C.** The sample is the quantity of matter contained in a surface on which the relative weighting factor is $1/e$.

The development of surfaces such as those defined is quite complicated mathematically, in general, but for purposes of illustration, the shape of some very simple specific examples, which are more easily derivable, will be considered.

Where both the neutron flux and the secondary gamma-ray flux are assumed to have very large penetrating power, such that neither one is appreciably absorbed in traveling a distance through the rock equal to the space between the source and the detector, there is a surface of equal weighting factor. It is a figure of revolution of which a section through the axis of rotation has the form

$$r^2 = 4a^2 \cos \theta - 2a^2$$

which is the degenerate lemniscate of a family of Cassinian ovals. Other surfaces corresponding with other weighting factors will be non-degenerate Cassinian ovals.

The surface shown in section in Fig. 4*a* (the inner curve) is one for which the weighting factor is equal to that prevailing at the midpoint between source and detector. Similar surfaces will exist in every case in which there is a consequential absorption coefficient. In such instances, it will be convenient to choose, for one of the examples in each case, those surfaces on which the weighting factor is one. Outer ovals are also shown corresponding to non-zero constrictions in the middle. These outer sections are, of course, drawn for fractional values of the weighting factor.

Figure 4*b* illustrates, in section through the axis of rotation, a surface corresponding to an arrangement in which both absorption coefficients are equal but relatively large.

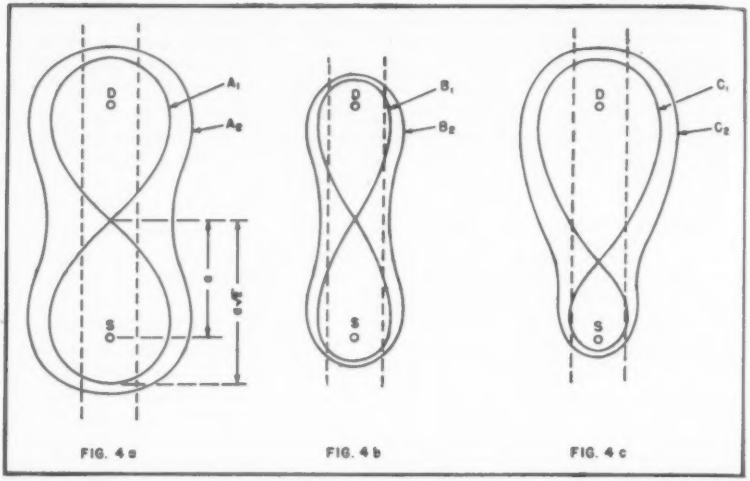



FIG. 4 a FIG. 4 b FIG. 4 c

**FIG. 4. In the surfaces of constant weighting factor for secondary-ray logging methods represented above, S is the source and D is the detector. Dotted lines indicate the position of the well bore—assumed to be filled with material whose nuclear properties are identical with the properties of the surrounding rock. The "figure-eight" curves ($A_1$, $B_1$, and $C_1$) represent longitudinal sections of surfaces for which the weighting factor is 1. $A_2$, $B_2$, $C_2$ are surfaces corresponding with fractional weighting factors. In Fig. 4*a*, it is assumed that the emitted and detected radiations have a very small absorption in passing a distance SD through the environment substance. Fig. 4*b* represents the case in which both the emitted radiation and detected secondary radiation are appreciably absorbed but equally so. Fig. 4*c* represents the case in which radiations from the source are more penetrating than those secondary radiations observed by the detector**

Figure 4*c* shows an example in which the emitted rays are more penetrating than the detected ones. This case more nearly corresponds to the situation which actually prevails in most neutron well-logging examples.

Sampling in neutron well logging cannot be quantitatively treated as was gamma-ray well logging (*1*) because of lack of accurate ranges of neutrons in rock substances. It is known experimentally, however, that the sampling secured by this method is very extensive and enables unusually representative data to be obtained on heterogeneous masses of material. This fact is illustrated by the graph on page 31. Here the neutron method clearly revealed the presence of an important amount of average pore space in a very heterogeneous fractured mass of Devonian chert. The good sampling achieved made possible a measurement of considerable value. Common methods of coring, on the other hand, fail to get representative samples, because only rock *within* the hole can be taken. In this particular case, the rock frequently coheres too poorly to enable cores to be removed at all. Somewhat similar gamma observations were made.

These propositions demonstrate another and more general conclusion of even greater importance: *Gamma-ray and neutron well logging are not substitutes for anything else, but are, in themselves and in combination, outstandingly useful measurements, and, within their most advantageous sphere of operation, are superior to other measurements.*

### Statistical Fluctuations

Because of the paucity of naturally occurring gamma rays, and because of the weakness of available capsuled sources of neutrons used in neutron well logging, both neutron and gamma-ray curves are affected by error due to statistical fluctuations. It is true that the total number of neutrons emitted by a feasible source is, of itself, sufficient to produce accurate measurements rapidly. Nonetheless, preferred arrangements for performing neutron well logging allow the observation of only a very small fraction of the total number of processes caused by these neutrons.

Lack of perfect duplication is, therefore, a general property of neutron and gamma-ray well logs. Obviously, in any case in which duplication is not sufficiently good to meet the requirements of the problem, it can be made better by making the measurements more slowly, or, in the case of the neutron logging, by using stronger sources. The practically attained quality of duplication in neutron well logging, for example, is an economic compromise involving the value of greater accuracy in the logging curve, cost of operating time, and expense of radiation source. Examples of commercially acceptable accuracy of duplication in neutron well logging are seen in Fig. 5 and the graph on page 31, which also show comparison between neutron and gamma-ray logs.

### Combined Use of Logs

One might think that the availability of a gamma-ray log would decrease the need for a neutron log on a given well, that one log is enough, or that the greater part of the information value will be obtained with the first curve, whatever its nature. Nothing could be farther from the truth. Perhaps, if an unlimited selection of different measurements were available, one would reach a point of diminishing returns

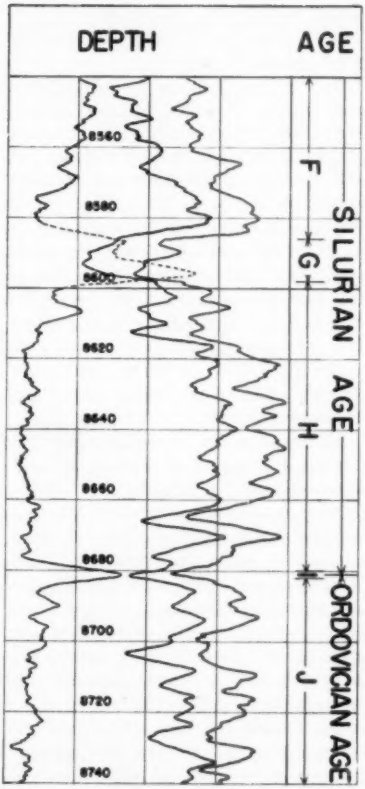



**FIG. 5. Gamma-ray and duplicated neutron curves for a well in TXL Field, Ector County, Texas. These logs show a very clear differentiation between fine sediments (zones G and I) and other rocks. Zones H and J are dolomites having insufficient footage of porous rock to produce commercial quantities of petroleum. Changes in the porosity throughout these zones are recorded and checked by the successive neutron curves. (*Courtesy of Lane-Wells, Co., Los Angeles*)**

where further measurements would not be justified. For the first several well-logging curves, another principle is preeminent, however. This is the principle of augmented value, by which each new measurement not only adds the specific meaning it was designed for,

but also permits a better understanding and a larger use of earlier well-logging curves or other data.

Neutron and gamma-ray curves when used in combination have a high augmentation value. It is as if several observers each gifted with vision were attempting to identify an object. Observer A can see and judge color. Observer B can determine if objects are rough or smooth. Observer C can tell form. All these observers cooperating can describe for us what they see. In well logging, similarly, we can report only one quality in any one curve; thus more than one curve is needed to describe the economically important qualities of rock strata satisfactorily.

The gamma-ray curve identifies fine shaly sediments by high radioactivity. Such sediments are rarely ever an important source of oil or gas. The remaining rocks, which show up as broad minima on the gamma-ray curve, are, in general, a minority of the sedimentary strata of the earth. They comprise the rock strata in which there may be petroleum, if pore spaces are present.* This urgent problem of recognizing the porous, fluid-filled zones which sometimes occur in non-shale rocks cannot be done by the gamma-ray curve because no differences in radioactivity are found to indicate fluid. This is the task of the neutron curve, which represents such zones as local minima in the broad maxima which otherwise correspond with these hard rocks in the neutron curve. The neutron curve, on the other hand, cannot differentiate between a thin shale zone and a porous zone, by itself. Both are minima. The gamma curve helps out here, since the shale is radioactive.

The search for oil is thus narrowed down to fluid-filled zones in rocks of a kind which could be productive. These clues, with some good guessing, based perhaps on adjoining wells or on reservoir characteristics of the given oilfield, are often enough to decide where the economic values are. If present trends of nuclear well logging continue, there may someday also be a means of telling what kind of fluid the strata contains and where the fluid *is* in the strata.

It is not impossible that as yet undeveloped nuclear methods may surpass neutron well logging as it surpasses the older and more imperfect driller's logs of early-day wildcat operators. The future is bright with hope for extended application of nuclear methods to the whole petroleum producing industry.

* * *

*The author expresses his thanks to Well Surveys, Inc. for use of its facilities in the preparation of this article, to Mr. Arthur Youmans and Mrs. Fearon for reading the manuscript, and to Mr. E. S. Mardock for help in preparing the well information.*

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* Existence of adequate pore space is the exception, not the rule. Also, occurrence of oil, rather than aqueous fluid is the exception. In this respect, petroleum is like other valuable minerals, the occurrence of which must nearly always be treated as a rare and exceptional phenomenon.

# Introduction to the Theory of Diffusion and Slowing Down of Neutrons—II*

**Before age theory is taken up in Parts III and IV, improvements on the diffusion theory, which include spherical-harmonic and integral-equation methods, are considered here. In the preceding portion of this paper on pile theory, the authors discussed derivation of the diffusion theory, solution of the Boltzmann equation, relation between point and plane sources, solutions of the diffusion equation, rigorous solution of the Boltzmann equation, and correction to the diffusion theory near boundaries.**

By R. E. MARSHAK,† H. BROOKS,‡ and H. HURWITZ, Jr.‡

## Spherical Harmonic Method (*12–16*)

WE HAVE SEEN that diffusion theory can be derived from the Boltzmann equation by expanding $N(z,\mu)$ in spherical harmonics in $\mu$ and keeping only the first two terms. If diffusion theory is not sufficiently accurate for a particular problem, it can be improved upon by keeping more terms in the expansion of $N(z,\mu)$. The accuracy of the results increases rapidly as more and more terms are retained. It is entirely feasible to keep ten or twelve terms in the expansion, but it is generally sufficient to keep considerably fewer.

This procedure is particularly useful for treating problems in which the scattering is anisotropic or which involve media having different total mean free paths since then other methods of treatment break down. (Problems involving media with different mean free paths in which the boundaries are all parallel planes can be reduced to problems in which the mean free paths are the same by a change of scale, but this is not possible for spheres and cylinders.)

We shall illustrate the spherical harmonic method by considering the problem of a plane slab of thickness $2d$ of one material bounded by an infinite "reflector" of a different material. For simplicity we assume that the mean free paths (*i.e.*, total cross sections) are the same in the two media. In general, as many terms may be kept in the expansion of the scattering function $F(\mu_0)$ (*cf.* Eq. 9) as are kept in the expansion of $N(z,\mu)$. However, for ease of presentation we assume that the scattering is isotropic so that the expansion of $F(\mu_0)$ consists rigorously of just one term. We also assume that the slab is made up of active (*i.e.*, fissionable) material and that the neutrons produced in a fission have just one velocity so that a one-velocity treatment is applicable.

The fissions can then be treated by a slight generalization of the fundamental Eq. 33 which may be written (assuming no source):

* This is the second of a series of four papers compiled from notes taken by H. Brooks and H. Hurwitz, Jr., on lectures given at the General Electric Company by R. E. Marshak during the summer of 1946. A large part of the work described was performed under the auspices of the Atomic Energy Project and thus will be presented in volumes of the National Nuclear Energy Series (Manhattan Project Technical Section).

Part I appeared in NUCLEONICS **4**, No. 5, 10 (1949); Parts III and IV will be published in succeeding months.

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$$\mu \frac{\partial N(z,\mu)}{\partial z} + \sigma N(z,\mu) = \sigma_s \frac{N_0(z)}{4\pi} \quad (71)$$

The term on the right-hand side of Eq. 71 represents the rate at which neutrons are being scattered into a unit solid angle. When fissions can occur, we must add on the right-hand side the rate at which neutrons are produced per unit solid angle by fissions. This is just $\nu\sigma_f(N_0/4\pi)$, where $\nu$ is the number of neutrons produced per fission. Hence Eq. 71 becomes:

$$\frac{\mu}{\sigma}\frac{\partial N(z,\mu)}{\partial z} + N(z,\mu) = \frac{\sigma_s + \nu\sigma_f}{\sigma}\frac{N_0(z)}{4\pi} \quad (72)$$

where

$$\sigma = \sigma_s + \sigma_c + \sigma_f \quad (73)$$

If $z$ is measured in units of $1/\sigma$, then Eq. 72 can be written

$$\mu \frac{\partial N(z,\mu)}{\partial z} + N(z,\mu) = (1 + f')\frac{N_0(z)}{4\pi} \quad (74)$$

The effect of fission is therefore just to change the sign of $f$. The equations for $N(z,\mu)$ in the two media are now:

$$\mu \frac{\partial N_a}{\partial z} + N_a = (1 + f')\frac{N_{a_0}}{4\pi} \quad (75)$$

$$\mu \frac{\partial N_b}{\partial z} + N_b = (1 - f)\frac{N_{b_0}}{4\pi} \quad (76)$$

where the subscripts $a$ and $b$ refer to the slab material and reflector material, respectively. We now expand $N_a(z,\mu)$ and $N_b(z,\mu)$ in spherical harmonics as in Eq. 10. If we use the recursion relation for Legendre polynomials

$$\mu P_l(\mu) = \frac{(l+1)P_{l+1}(\mu) + lP_{l-1}(\mu)}{2l+1} \quad (77)$$

Eqs. 75 and 76 become:

$$\sum_{l=0}^{\infty} \frac{dN_{a_l}(z)}{dz}[P_{l+1}(\mu)(l+1) + lP_{l-1}(\mu)] + \sum_{l=0}^{\infty} N_{a_l}(z)P_l(\mu)(2l+1) = (1+f')N_{a_0}(z) \quad (78)$$

and there is a similar set of equations for the $N_{b_l}(z)$. If we now compare the coefficients of $P_l(\mu)$ on the two sides of the equations, we obtain a set of total differential equations:

$$\frac{dN_{a_1}(z)}{dz} + N_{a_0}(z) = (1+f')N_{a_0}(z)$$

$$\frac{dN_{a_0}(z)}{dz} + 2\frac{dN_{a_2}(z)}{dz} + 3N_{a_1}(z) = 0$$

$$2\frac{dN_{a_1}(z)}{dz} + 3\frac{dN_{a_3}(z)}{dz} + 5N_{a_2}(z) = 0 \quad (79)$$

and similarly for the $N_{b_l}(z)$. Let us try to solve these coupled differential equations by trying a solution of the form:

$$N_{a_l}(z) = N_{a_l}(k)e^{kz} \quad (80)$$

where the quantities $N_{a_l}(k)$ are constants. Substitution into Eqs. 79 leads to a set of linear equations for $N_{a_l}(k)$ with coefficients depending on $k$:

$$\begin{aligned} kN_{a_1}(k) + N_{a_0}(k) &= (1+f')N_{a_0}(k) \\ kN_{a_0}(k) + 2kN_{a_2}(k) + 3N_{a_1}(k) &= 0 \\ 2kN_{a_1}(k) + 3kN_{a_3}(k) + 5N_{a_2}(k) &= 0 \\ 3kN_{a_2}(k) + 4kN_{a_4}(k) + 7N_{a_3}(k) &= 0 \end{aligned} \quad (81)$$

Thus we have an infinite set of linear equations to solve. In order to obtain simple solutions, we neglect (*i.e.*, assume equal to zero) those $N_{a_l}(k)$'s for which $i$ is greater than a certain value $i_0$. In practice, it is convenient to let $i_0$ be an odd number. If $i_0 = 1$ we obtain results equivalent to simple diffusion theory. For higher values of $i_0$ the method gives more accurate results. If, for example, $i_0$ is taken to be three, then Eq. 81 reduces to four linear equations for the four quantities $N_{a_0}(k)$ . . . $N_{a_3}(k)$. If these equations are to be consistent, the determinant must vanish:

$$\begin{vmatrix} -f' & k & 0 & 0 \\ k & 3 & 2k & 0 \\ 0 & 2k & 5 & 3k \\ 0 & 0 & 3k & 7 \end{vmatrix} = 0 \quad (82)$$

Equation 82 yields a quadratic equation for $k^2$. If $f'$ is positive, one of the roots will be positive and the other negative. Hence there will be a pair of real values and a pair of imaginary values of $k$ for which solutions of the form Eq. 80 can be found. Once the allowed values of $k$ have been determined, it is an easy matter to solve Eq. 81 for the quantities $N_{a_i}(k)$. One thus obtains four solutions of Eq. 79, two varying exponentially with $z$ and two being oscillatory functions of $z$. In region $b$ the situation differs only in that $f'$ is replaced by $-f$. The eigenvalues of $k^2$ are then both real so that one obtains four exponential solutions.

In general, if $i_0$ is taken to be equal to $2l - 1$, the equation corresponding to Eq. 82 will be satisfied by $l$ different values of $k^2$. When $f$ is positive (capturing medium), all the eigenvalues of $k^2$ are positive so that all the solutions vary exponentially. When $f' = -f$ is positive (multiplying medium), there will be one negative eigenvalue of $k^2$ which corresponds to an oscillatory solution. In the limit of $i_0$ approaching infinity, the lowest eigenvalue of $k$ in the case of positive $f$ and the imaginary eigenvalue of $k$ in the case of positive $f'$ approach the roots of the equations

$$\frac{k}{\text{arctanh } k} = 1 - f \qquad (83)$$

and

$$\frac{k/i}{\arctan k/i} = 1 + f' \qquad (84)$$

respectively. Note that these equations are equivalent to Eq. 40. The other eigenvalues of $k$ are closely related to the continued fraction expression for $\tanh^{-1} k$. They are tabulated for various values of $i_0$ and $f$ (or $f'$) in reference *15*.*

The boundary condition to be applied at interfaces in the spherical harmonic method is that the coefficients in the expansion of $N(z,\mu)$ in Legendre polynomial must be continuous. In diffusion theory, where only two terms are retained, this amounts to requiring continuity of the neutron density and neutron current. We shall show that for a general odd value of $i_0$ the above boundary conditions are adequate to determine the solution of the slab problem.

In the "reflector" we must take exponential solutions which go to zero at infinity. Thus, for a particular value of $i_0 = 2l - 1$, there are $l$ possible values of $k$ so that the general solution involves $l$ arbitrary constants.

In the slab, symmetry requires that the solution corresponding to a particular value of $k$ appear with the same coefficient as the solution corresponding to $-k$. The general solution will, therefore, again contain only $l$ arbitrary constants. (Note that for the solution corresponding to the imaginary value of $k$, the $N_i(z)$ will be cosine or sine functions depending on whether $i$ is even or odd. Thus, for example, neutron density $N_0$ will be an even function of $z$, whereas current density $N_1$ will be an odd function of $z$.) In all, we therefore have $2l$ arbitrary constants.

Since we have already used the requirement of symmetry, it is sufficient to satisfy the boundary condition at one interface. We must require that the functions $N_0(z), N_1(z) \ldots N_{i_0}(z)$ all be continuous at $z = d$. This gives us $i_0 + 1 = 2l$ equations for the $2l$ arbitrary constants. Since these equations will be homogeneous, we must require that the associated determinant vanishes. This will give a relation between $f$, $f'$ and $d$. There must be such a relationship on physical grounds since we have required that the solution be time independent (*i.e.*, that the system be critical). The relation between $f$, $f'$ and $d$ may be used to determine the "critical size" of the slab as a function of $f$ and $f'$. Note that, if the materials on the two sides of the slab were different, the general solution would contain $4l$ arbitrary

* See bibliography in Part I.

constants ($l$ constants for each half of the reflector, and $2l$ constants in the slab itself). Since the problem would then not have symmetry about $z = 0$, the boundary conditions at the two interfaces would give independent relations so that one would have $4l$ equations for $4l$ unknowns.

In applying the spherical harmonic method to problems involving spherical symmetry, $\mu$ is defined as the cosine of the angle between the direction of motion of the neutron and the position vector of the neutron. The fundamental equation is then (assuming isotropic scattering):

$$\mu \frac{\partial N}{\partial \mu} + \frac{(1 - \mu^2)}{r} \frac{\partial N}{\partial \mu} + N = \frac{1 - f}{4\pi} N_0 \quad (85)$$

Starting from this equation one proceeds exactly as in the plane case. For a given value of $i_0$ one obtains solutions of the form

$$N_i \sim \frac{e^{kr}}{r} \quad (86)$$

with values of $k$ which are exactly the same as for the plane case. It is clear that this must be so since by compounding plane solutions with the same value of $k$, but different axes of symmetry, one can form solutions similar to Eq. 86.

### Integral Equation Methods

In one-velocity problems where the neutron mean free path is the same throughout space and the scattering is isotropic, it is convenient to make use of the rather simple integral equation which then holds for the neutron density $N_0(\mathbf{r})$ [which we shall hereafter write simply $n(\mathbf{r})$] (*17, 1*).

To derive this equation, let us consider a neutron which starts out at a point $\mathbf{r}_0$. The neutron will move in a straight line until it suffers a collision. The probability that the neutron will not have suffered a collision after moving a distance $l$ is $e^{-\sigma l}$ where $\sigma$ is the total cross section measured in cm$^{-1}$. The probability that the neutron suffers its first collision in the interval $dl$ is $\sigma e^{-\sigma l} dl$. If we consider a spherical shell of radius $l$ and thickness $dl$ around the point $\mathbf{r}_0$, we can say that the probability that the neutron suffers its first collision in the shell is

$$\sigma e^{-\sigma l} dl = \frac{\sigma e^{-\sigma l}}{4\pi l^2} dV \quad (87)$$

where $dV$ is the volume of the shell. The quantity $\frac{\sigma e^{-\sigma l}}{4\pi l^2}$ can clearly be interpreted as the probability per unit volume that the neutron suffers its first collision in a small region a distance $l$ from the point at which it starts out. It therefore follows that, if $Q(\mathbf{r}')d\mathbf{r}'$ represents the number of neutrons that start out in a volume element $d\mathbf{r}'$ per unit time, the number of first collisions which occur per unit volume at the point $\mathbf{r}$ is:

$$N(\mathbf{r}) = \int\int\int d\mathbf{r}' Q(\mathbf{r}') \frac{\sigma e^{-\sigma|\mathbf{r} - \mathbf{r}'|}}{4\pi|\mathbf{r} - \mathbf{r}'|^2} \quad (88)$$

Equation 88 refers so far only to first collisions. However, we can generalize it to include all collisions by a simple artifice. Let us imagine that whenever a neutron suffers a collision it is destroyed and $1 - f$ new neutrons appear. For a scattering collision, $f$ would be zero; for a capture, $f = +1$; and for a fission, $f = 1 - \nu$. From this viewpoint all collisions are first collisions, and we have an additional source of neutrons of $(1 - f)N(\mathbf{r})$ per unit volume. Hence, Eq. 88 becomes

$$N(\mathbf{r}) = \int\int\int d\mathbf{r}' Q(\mathbf{r}') \frac{\sigma e^{-\sigma|\mathbf{r} - \mathbf{r}'|}}{4\pi|\mathbf{r} - \mathbf{r}'|^2} + \int\int\int d\mathbf{r}' N(\mathbf{r}')[1 - f(\mathbf{r}')] \frac{\sigma e^{-\sigma|\mathbf{r} - \mathbf{r}'|}}{4\pi|\mathbf{r} - \mathbf{r}'|^2} \quad (89)$$

(We are here allowing $f$ to be a function of position, but $\sigma$ is still assumed constant). Since $N(\mathbf{r}) = n(\mathbf{r})\nu\sigma$, Eq. 89 can be rewritten as follows:

$$n(\mathbf{r}) = \iiint d\mathbf{r}' Q(\mathbf{r}') \frac{\sigma e^{-\sigma|\mathbf{r}-\mathbf{r}'|}}{\nu 4\pi|\mathbf{r}-\mathbf{r}'|^2} + \iiint d\mathbf{r}' n(\mathbf{r}')[1 - f(\mathbf{r}')] \frac{\sigma e^{-\sigma|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|^2} \quad (90)$$

When scattering, absorption, and fission collisions can all occur at the same point, we must use an average value for $f(\mathbf{r})$:

$$f(\mathbf{r}) = 1 - \frac{\sigma_s(\mathbf{r}) + \nu\sigma_f(\mathbf{r})}{\sigma(\mathbf{r})} \quad (91)$$

or, since $\sigma = \sigma_s + \sigma_f + \sigma_c$ (92)

we have

$$f(\mathbf{r}) = \frac{\sigma_c(\mathbf{r}) - (\nu - 1)\sigma_f(\mathbf{r})}{\sigma(\mathbf{r})} \quad (93)$$

(Note that $f$ has the same meaning that it had in previous equations.)

It is quite easy to extend the integral equation to the time dependent case (*17*). By a generalization of the argument given above, we find that Eq. 90 becomes that equation shown at the bottom of the page (Eq. 94). We have used the fact that the number of first collisions occurring at a distance $l$ from a source at time $t$ depends on the source strength at time $t - (l/v)$. If we assume that $Q(\mathbf{r},t)$ and $n(\mathbf{r},t)$ vary exponentially, *i.e.*,

$$n(\mathbf{r},t) = n(\mathbf{r})e^{\alpha t}$$
$$Q(\mathbf{r},t) = Q(\mathbf{r})e^{\alpha t} \quad (95)$$

then the integral equation becomes:

$$n(\mathbf{r}) = \iiint d\mathbf{r}' \frac{Q(\mathbf{r}')}{\nu} \frac{e^{-\left(\sigma+\frac{\alpha}{v}\right)|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|^2} + \iiint d\mathbf{r}' n(\mathbf{r}')[1 - f(\mathbf{r}')] \frac{\sigma e^{-\left(\sigma+\frac{\alpha}{v}\right)|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|^2} \quad (96)$$

This equation is very similar to the time independent Eq. 90. The extra term $\alpha/v$ which is added to $\sigma$ in the exponent is referred to as the "time absorption" term.

If no sources are present, Eqs. 90 and 96 can be written in the form:

$$n(\mathbf{r}) = \iiint d\mathbf{r}' \tau(\mathbf{r}') n(\mathbf{r}') K(|\mathbf{r} - \mathbf{r}'|) \quad (97)$$

where $$\int_0^\infty K(r) 4\pi r^2 dr = 1 \quad (98)$$

In the general time dependent case

$$K(r) = \frac{\sigma + \frac{\alpha}{\nu}}{4\pi r^2} e^{-\left(\sigma+\frac{\alpha}{v}\right)r}$$
$$\tau(\mathbf{r}) = \frac{1 - f(\mathbf{r})}{1 + \frac{\alpha}{\sigma v}} \quad (99)$$

Integral equations of the form of Eq. 97 are encountered frequently in pile theory. Problems involving more than one neutron velocity may sometimes be reduced to this form with kernels different from Eq. 99. (The kernel $K(r)$ appearing in Eq. 99 is referred to as the Milne kernel.) In problems where $n(\mathbf{r})$ and $\tau(\mathbf{r})$ are functions of $z$ only, Eq. 97 becomes:

$$n(z) = \int_{-\infty}^{+\infty} dz' \tau(z') n(z') K_1(|z - z'|) \quad (100)$$

where

$$K_1(z) = 2\pi \int_{|z|}^\infty RK(R)dR \quad (101)$$

Hence for the Milne kernel with $\sigma = 1$, ($\alpha = 0$):

$$K_1(z) = \frac{1}{2} \int_{|z|}^\infty \frac{e^{-z'}}{z'} dz' \quad (102)$$

A useful theorem which can easily be proved in connection with integral equations of the form of Eq. 97 is that problems with spherical symmetry (*i.e.*,

$$n(\mathbf{r},t) = \iiint d\mathbf{r}' \frac{Q\left(\mathbf{r}', t - \frac{|\mathbf{r}-\mathbf{r}'|}{v}\right) e^{-\sigma|\mathbf{r}-\mathbf{r}'|}}{\nu 4\pi|\mathbf{r}-\mathbf{r}'|^2} + \iiint d\mathbf{r}' n\left(\mathbf{r}', t - \frac{|\mathbf{r}-\mathbf{r}'|}{v}\right)[1 - f(\mathbf{r}')] \frac{\sigma e^{-\sigma|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|^2} \quad (94)$$

$n,\tau$ functions of $r$ alone) can be related to problems with plane symmetry ($n,\tau$ functions of $z$ alone) according to the following scheme:

| *Spherical Problem* | | *Plane Problem* |
|---|---|---|
| $\tau_s(r)$ | $\longleftrightarrow$ | $\tau_p(z) = \tau_s(\|z\|)$ |
| $n_s(r)$ | $\longleftrightarrow$ | $n_p(z) = zn_s(\|z\|)$ |

Thus the neutron density times the radius in the spherical problem is equal to the neutron density in the corresponding plane problem.

It is important to note that in the equivalent plane problem the neutron density must be an odd function of $z$, i.e., $n_p(-z) = -n_p(z)$. As an example, the problem of a sphere of radius $a$ with an infinite reflector is related to the problem of a slab of thickness $2a$ with an infinite reflector on each side. This does not mean that the critical radius of a sphere is half the critical thickness of a slab, because in the equivalent slab problem the neutron density is required to be an odd function of $z$, whereas, in the actual physical problem for a slab, the neutron density is an even function of $z$. Despite the somewhat artificial nature of the equivalent slab problem, it is of considerable help since it enables one to deal with plane rather than spherical geometry.

A powerful method for dealing with integral equations of the form of Eq. 97 and related forms is the variational method (*18*, *19*). This method may be applied no matter how complicated the geometry and kernels may be. (The kernel need not even be a function of the distance between $\mathbf{r}$ and $\mathbf{r}'$ alone. The only requirement is that it be symmetrical.) In critical mass problems one has known values of $\tau$ and wishes to find the configuration which will make the system critical. It is usually simpler, however, to assume a geometry and try to find the values of $\tau$ which will make the geometry critical. By comparing these values of $\tau$ with the actual values, one can tell whether the particular geometry is over or under critical. If such a procedure is carried through for a few different geometries it is usually possible to make an extrapolation or interpolation to find the critical geometry. Let us, therefore, assume that $\tau(\mathbf{r}) = (1/\lambda)\tau_0(\mathbf{r})$, where $\lambda$ is to be determined. Then Eq. 97 becomes:

$$\lambda n(\mathbf{r}) = \iiint d\mathbf{r}'\tau_0(\mathbf{r}')n(\mathbf{r}')K(|\mathbf{r} - \mathbf{r}'|) \quad (103)$$

If we multiply by $\tau_0(\mathbf{r})n(\mathbf{r})$ and integrate over all space, we find:

$$\lambda = \frac{\int \ldots \int d\mathbf{r}d\mathbf{r}'\tau_0(\mathbf{r})\tau_0(\mathbf{r}')n(\mathbf{r})n(\mathbf{r}')K(|\mathbf{r} - \mathbf{r}'|)}{\iiint \tau_0(\mathbf{r})n^2(\mathbf{r})d\mathbf{r}} \quad (104)$$

It can be easily shown that the integral equation (103) for $n(\mathbf{r})$ is equivalent to the requirement that the variation of the quantity on the right-hand side of Eq. 104 for small variations in $n(\mathbf{r})$ be zero. This means that even if rather poor approximations to the actual solution are substituted into the right-hand side of Eq. 104, one will still obtain a fairly good value for $\lambda$. For example, with a very complicated geometry one might divide the system up into small regions in which $n(\mathbf{r})$ could be assumed to be constant. The values of the constants in the small regions then could be determined to extremize Eq. 104. This procedure is feasible in practical problems which cannot be treated by other methods. In problems in which $\tau_0(\mathbf{r})$ is constant in a sphere, and zero outside, it is often sufficient to use a parabolic trial function in the variational expression Eq. 104, *e.g.*

$$n(r) = 1 - kr^2 \quad (105)$$

The constant $k$ is chosen to extremize Eq. 104.

Another powerful means of treating integral equations of the form of Eq. 97 is the Wiener-Hopf method.

This method can be applied directly to the problem of two semi-infinite media with a plane interface (*20*, *21*). The pertinent integral equation is then of the form of Eq. 100 with

$$\tau(z) = \tau_1 \qquad z < 0$$
$$\tau(z) = \tau_2 \qquad z > 0 \qquad (106)$$

If $\tau(z)$ were entirely independent of $z$, then Eq. 100 would have a solution of the form

$$n(z) = Ae^{kz} + Be^{-kz} \qquad (107)$$

where

$$1 = \tau \int_{-\infty}^{+\infty} \cosh kz K_1(z)dz \qquad (108)$$

If $\tau$ is smaller than one (non-multiplying medium), $k$ is real: while if $\tau$ is larger than one (multiplying medium), $k$ is imaginary so that the solutions may be written as sine and cosine functions. In the two-media problem described by Eq. 106, the asymptotic solution for large and small $z$ will still have the form Eq. 108. Thus:

$$n(z) = A_1e^{k_1z} + B_1e^{-k_1z} \qquad z \ll 0$$
$$n(z) = A_2e^{k_2z} + B_2e^{-k_2z} \qquad z \gg 0 \qquad (109)$$

By means of the Wiener-Hopf method, one can find $A_2$ and $B_2$ in terms of $A_1$ and $B_1$ for a large class of kernels which may be expressed in analytical form (*20–23*). For example, if region 1 is non-multiplying and region 2 is multiplying, then (if we require that $n(z) \to 0$ as $z \to -\infty$) the solution will have the asymptotic forms:

$$n(z) = ae^{k_1z} \qquad z \gg 0$$
$$n(z) = b \sin |k_2|(z + z_0) \qquad z \gg 0 \qquad (110)$$

One can then calculate $z_0$ as a function of $\tau_1$ and $\tau_2$.

For the Milne kernel which corresponds to the one-velocity neutron-diffusion problem, the value of $k$ determined by Eq. 108 with $\tau = 1 - f$ is the same as that determined by Eqs. 83 and 84. In reference *20*, the relations between $A_1$, $B_1$, $A_2$, and $B_2$ in Eq. 109, which one obtains by the Wiener-Hopf method, are expressed by saying that one equates the logarithmic derivative of the asymptotic solution for negative $z$ at the point $z = z_1$ to the logarithmic derivative of the asymptotic solution for positive $z$ at the point $z_2$. The quantities $z_1$ and $z_2$ are functions of $\tau_1$ and $\tau_2$. On the basis of simple differential diffusion theory, one would take $z_1$ and $z_2$ to be zero. The fact that they are not equal to zero arises from the fact that the mean free path is finite.

To treat plane problems involving more than two media by the Wiener-Hopf method, one makes the approximation that the different interfaces are far enough apart so that one can treat the problem for each interface separately. Thus at each interface one obtains a relation between the coefficients in the asymptotic solutions in the two adjoining media. Consider, for example, the problem of a slab of one material of thickness $2d$ with an infinite reflector of a different material. The solution in the slab will be:

$$n = a \cos k_s z$$
$$= a \sin k_s \left( [z - d] + d + \frac{\pi}{2k_s} \right) \qquad (111)$$

and in the reflector

$$n = be^{-k_s z} \qquad (112)$$

Hence, by comparison with Eq. 103, one can relate $d + (\pi/2k_s)$ to $z_0$, which can be calculated so that the critical thickness of the slab is obtained.

To treat problems of spherical symmetry, one solves the equivalent plane problem in the manner just described. This gives results of sufficient accuracy for most purposes.

## BIBLIOGRAPHY

*Bibliography items referred to in the preceding text can be found in the complete bibliography published with Part I of this series of papers;* see NUCLEONICS **4**, No. 5, 22 (1949).

# Pulse Height Distribution Analyzer

**At the screen end of a cathode ray tube are placed targets to which are connected mechanical registers through a proper amplifying system. The height of the beam in the tube is controlled by the energy of alpha particles produced in an ion chamber. System is not bothered by drift, is faster and more easily stabilized than conventional biased-tube systems**

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AN INVALUABLE TOOL for the study of radioactive isotopes is the pulse analyzer, a device which makes it possible to plot alpha particle energy against the number of particles emitted of that energy. Since a radioactive element which emits alpha particles emits them in discrete energies, it is possible to detect the presence of extremely small quantities of such elements by analyzing the pulse height distribution of the pulses from an ionization chamber in which the sample has been placed. This is analogous to detecting the presence of an element by its light or X-ray spectrum with the light or X-ray energy replaced by the alpha particle energy.

Currently used pulse analyzers consist of an ionization chamber, pulse height selector, and a battery of registers to record the data. The pulses from the chamber have a height proportional to the energy of the alpha particle causing the pulse. These pulses are then separated into groups of pulse between two predetermined pulse heights by a series of biased tubes. The number of pulses in each group is then counted by a mechanical register. This gives a plot of the number of pulses of a given pulse height against the pulse height. This is also a plot of the number of alpha particles of a given energy against the energy of the particle.

One of the outstanding difficulties with present pulse analyzers is that of the drift of individual channels because of a drift in bias or tube characteristic in that channel. This is a much more serious difficulty than that of drift of the whole system, since it will give a false peak in the alpha spectrum which cannot be distinguished from a peak due to a radioactive isotope. By the use of a cathode-ray-tube pulse height selector, shown in Fig. 1, this difficulty can be eliminated.

The ionization chamber pulse *a* to be analyzed is shaped so that it has a flat top *b* and is applied to the deflection electrode *A* of the cathode-ray gun. The electron beam, which is normally off, is turned on at the peak of the pulse by a square pulse applied to the intensity grid *B* of the electron gun. The beam is then turned on at a position corresponding to the height of the applied pulse. A series of anodes *C* across the screen of the cathode-ray-tube collect the current from the beam, and a series of mechanical registers *D* count the number of times the beam strikes a given plate. This gives a count of the number of pulses which occur between two given pulse heights.

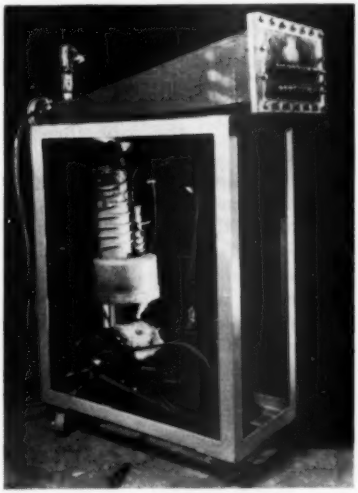
Since the channel width and relative position are a function only of the physical width and position of the anodes in the tube, there can be no individual register drift. This type of pulse height selection has the added advantages of being faster and more easily stabilized than the conventional system using biased tubes.

### Ionization Chamber

The purpose of the ionization chamber is to give pulses of a height proportional to the energy of the alpha particle being analyzed.*

There are two types of ionization chambers in common use with pulse analyzers: the two-electrode chamber and the grid chamber shown in Figs. 2*a* and *b* respectively. The particular two-electrode chamber and grid chamber used with the present pulse analyzer was designed by A. Ghiorso of the University of California Radiation Laboratory.

The chamber is filled with argon at a



**Pulse analyzer tube and pump**

* For a complete discussion of the ionization chamber see S. A. Korff, "Electron and Nuclear Counters," (D. Van Nostrand Company, New York, 1946).

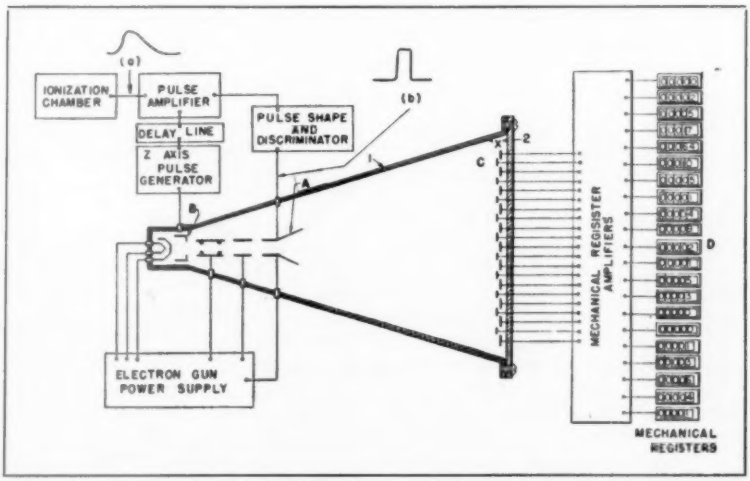



**FIG. 1. Arrangement of mechanical registers, and actual application of pulses to the cathode ray beam tube**

little above atmospheric pressure, and the sample to be analyzed is placed at *a*. The alpha particles emitted from the sample expend their energy in ionizing the gas *b*.

A circuit for the chamber is shown in Fig. 3*a*. Resistance *R* is of the order of 10 to 1,000 megohms, so that the decay time of the circuit is long compared to the rise time of the pulse from the chamber.

The negative ions, which in gases such as argon are free electrons, are attracted to the anode. The drift of these ions changes the charge on the chamber capacitance and, consequently, the voltage across it. The voltage pulse on the anode then rises to its maximum as the electrons are collected, and then decays very slowly, exponentially, with the time constant of the circuit.

The electrons are collected much faster than the positive ions because of their higher mobility. In the short period of time considered, the change in voltage caused by the drift of positive ions is quite small.

The height of the output pulse is approximately proportional to the total charge collected, which is approximately proportional to the energy of the alpha particle.

The shape of the output pulse is shown in Fig. 3*b*.

Some of the errors causing poor resolution in such a chamber are:

(*1*) Improper gas mixture, causing poor ionization properties;
(*2*) Variation in pulse height because of ions drifting different distances as a result of alpha particles being emitted at different angles;
(*3*) Positive ion drift affecting the anode voltage;
(*4*) Difficulty in amplifying the pulse accurately.

The second and third difficulties may be overcome by using a grid chamber as shown in Fig. 2*b*. This type of chamber has the anode *b* shielded from the effect of the positive ion drift by the grid *a*. The electrons all drift the same distance and through the same difference of potential between *a* and *b*.

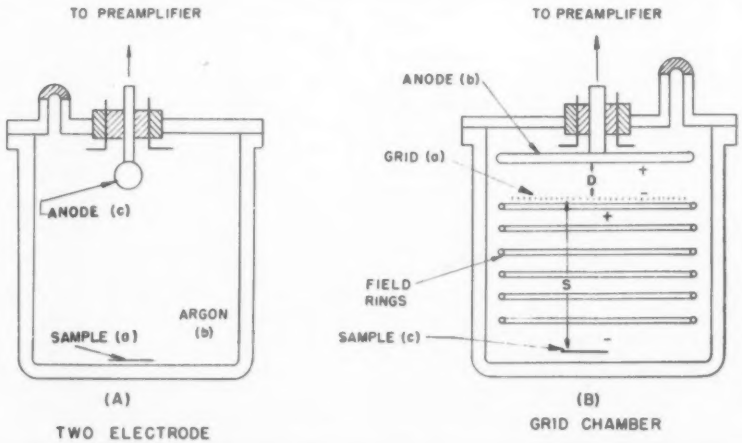



**FIG. 2. Types of ionization chambers used with the pulse height analyzer**

Consequently, the pulse height is more closely proportional to the total number of electrons, regardless of the position at which the ions are formed.*

Both types of ion chambers have been used with the pulse analyzer with little difference in results. The two-electrode chamber has been used more frequently because of its simplicity.

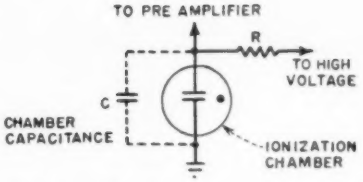



**FIG. 3*a*. Circuit for use with chamber**

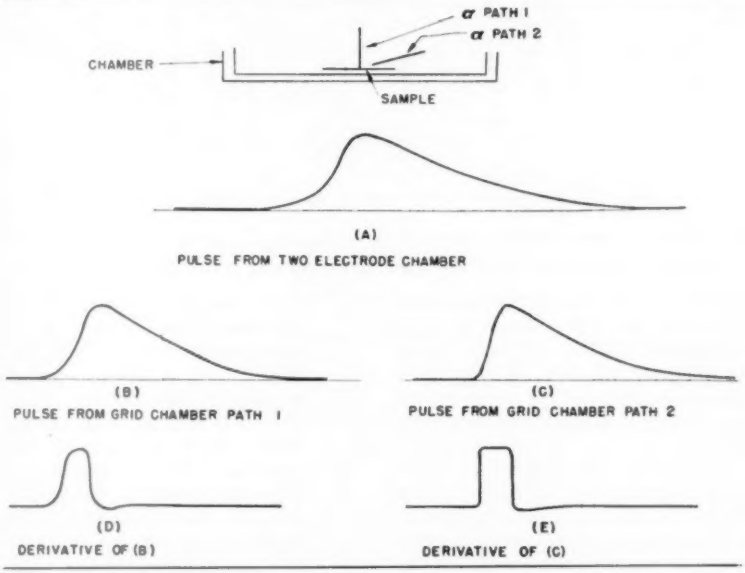



**FIG. 3*b*. Wave form of pulses secured from the ionization chamber**

### Preamplifier

Since the pulse from the ionization chamber is only of the order of a millivolt, it is necessary to have a preamplifier on the chamber to amplify the signal from the chamber to a high enough voltage to be handled easily in the following circuits. Because of the shapers that follow the preamplifier, it is necessary to preserve the shape of the pulse very accurately. Since the instrument is measuring small differences in pulse height, it is necessary that the gain of the amplifier be very constant and the signal-to-noise ratio be very high.

The pulse from the ionization chamber is a triangular pulse as shown in Fig. 3*b* with a rise time of the order of 10 μsec and a decay time of several milliseconds.

The rise time is determined by the transit time of the electrons in the ionization chamber, and the decay time

* For a complete discussion of grid chambers see O. Bunemann, T. E. Cranshaw, J. C. Harvey, "The Use of Grid Chambers for Alpha-Ray Analysis" (National Research Council of Canada, Montreal, May 1, 1946), CRP-247.

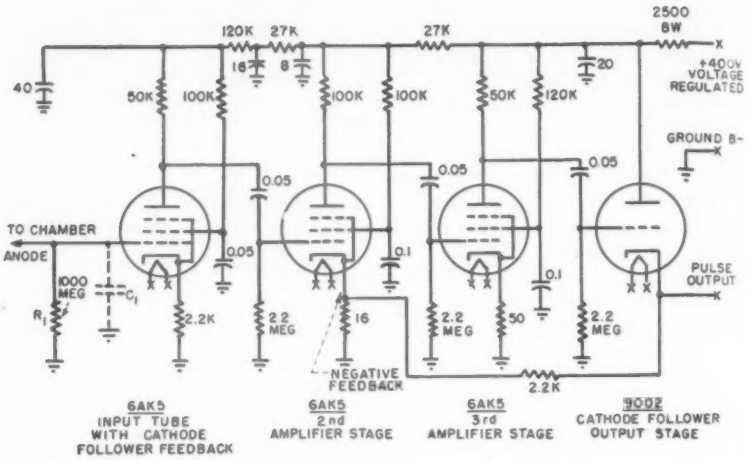



**FIG. 4. Circuit diagram of the preamplifier following the ionization chamber**

is determined by the $R_1C_1$ time constant of the anode, where $R_1$ is the input resistance of the amplifier and $C_1$ is the tube input and chamber capacitance shown in Fig. 4. To preserve this pulse shape, a pass band of from about 20 cycles to about 2 Mc is necessary.

A number of input tubes and input circuits were tried. The most satisfactory tube for signal-to-noise ratio was a 6AK5 connected as a pentode with a low plate voltage, as shown in Fig. 4.

The hum level was reduced by using a d-c filament supply and a well-filtered, doubly regulated power supply. To add to the stability, the filament supply is regulated by shunting it with a storage battery.

### Pulse Shaper and Discriminator

After the pulse from the ionization chamber has been amplified, it is a broad triangular pulse as shown at (a) in Fig. 5*b*. The pulse must then be shaped for two reasons:

(*1*) Since the pulse has a long decay time, a second pulse occurring before the first has returned to zero voltage will register an incorrect pulse height. It is therefore necessary to have the pulse return to zero as soon as possible.

(*2*) Since the random noise is uniformly distributed over all frequencies, it has an r-m-s amplitude proportional to the square root of the bandwidth. The signal-to-noise ratio will therefore be increased if the pulse height is preserved and the bandwidth of the shaper is reduced.

Two methods of shaping the pulse are in common use. The less satisfactory method of shaping, although it is much simpler, is a differentiating circuit.

The derivative of the applied pulse is obtained by applying the pulse to an *RC* circuit and taking the derivative of the pulse across the resistor.

For this to be a good approximation of the derivative, the time constant of the circuit must be short compared with the rise time of the applied pulse. The circuit may be used only if the maximum slope of the leading edge of the

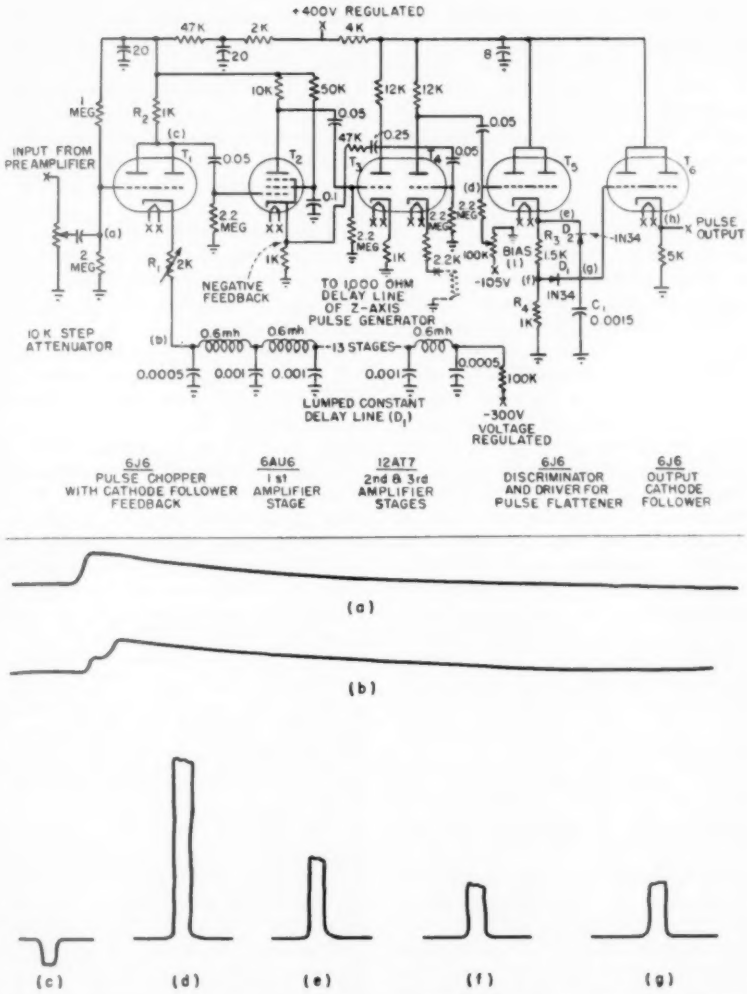



**FIG. 5*a*. (Above) Pulse-shaping circuit; (*b*). (Below) Wave forms of the pulses as shaped by the shaping circuits**

pulse is proportional to the energy of the alpha particle causing it. This is true to a high degree of accuracy only in the grid chamber of Fig. 2*b*.

The second method of pulse shaping is much more satisfactory because it gives a higher signal-to-noise ratio and gives a pulse shape which is much easier to handle. A circuit designed for this type of shaping is shown in Fig. 5*a*.

The pulse is applied to the grid (a) of the 6J6 shaper. Since the cathode follower has an impedance from cathode to ground of about 100 ohms the cathode potential will rise to approximately the grid potential. The characteristic impedance of the lumped constant delay line ($D_1$) is 1000 ohms. Resistance $R_1$ is adjusted so that the output impedance from point (b) to ground without the delay line connected is 1000 ohms. When the pulse is applied to the grid of the 6J6 the voltage across the delay line will rise to half the grid voltage. The signal reflects from the open end of the delay line 22 μsec later in the same phase as the applied pulse. The voltage at point (b), therefore, will rise to the full grid voltage 22 μsec later, after the signal has traversed the delay line and returned. Since the impedance across the input of the delay line is its characteristic impedance, there will be no further reflections. The voltage appearing across $R_1$, and consequently across $R_2$, will be the difference of the voltages at (a) and (b). This difference is a square pulse (c), which has a height proportional to the height of the input pulse and a pulse width of twice the delay time of the delay line.

The signal-to-noise ratio of the signal is increased by this type of shaper, since it attenuates the low frequencies. The frequency response for low frequencies (about a tenth the reciprocal of the delay time) is approximately proportional to the frequency. This attenuation of the low frequencies not only reduces the r-m-s value of the random noise but also greatly attenuates hum and tube microphonic noise.

For satisfactory amplification of a short square pulse there must be a wide pass band. Attenuation of the low frequencies produces a back kick on the pulse and attenuation of the high frequencies rounds the corners of the pulse. There must, therefore, be a pass band of from about 20 cycles to about 1 Mc.

The three amplifier stages which follow the delay line pulse shaper 6J6 ($T_1$) have negative feedback from the second stage ($T_2$) to the first ($T_2$) and the third stage ($T_4$) has cathode stabilization.

It is imperative that the pulse output be perfectly flat on top for the cathode-ray analyzer tube, since the beam must be stationary at the peak of the pulse while it is turned on.

To insure that the pulse is flat on top but with its height still preserved, a pulse flattener circuit was developed. In this circuit, shown in Fig. 5*a*, the pulse is applied to a cathode follower ($T_5$), and the pulse voltage is divided by $R_3$ and $R_4$ in the cathode circuit. The pulse appearing at point (f) will be a constant fraction of that appearing at (e). When the pulse rises to its maximum, $C_1$ will be charged by current through the crystal diode, $D_1$, to the maximum voltage of the pulse at point (f). This maximum occurs at the leading edge of the pulse. The voltage across $C_1$ will remain at this potential until it is lowered to zero by current through the diode, $D_2$, at the trailing edge of the pulse. The polarity of the diodes is such that while the pulse is at its top there is no current through either diode to $C_1$, since point (f) will be at a lower potential than point (g) after the leading edge of the pulse, and point (e) will be at a higher potential until the trailing edge of the pulse. This circuit, therefore, gives a pulse output which is flat on top and has a pulse height proportional to that of the input pulse.

Since it is usually desirable to analyze pulses above a certain height, a discriminator is incorporated in the circuit to make it possible for the circuit to handle the part of the pulse above a given voltage. This is done merely by applying a negative bias (i) to

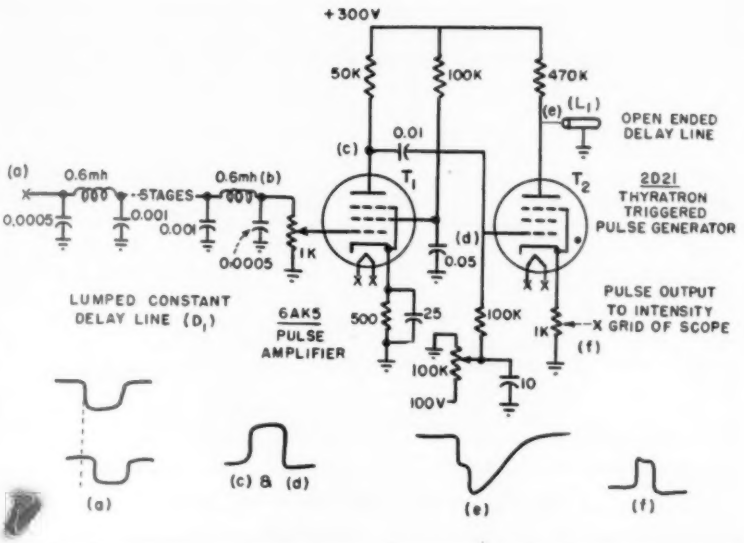



**FIG. 6. Z-axis pulse generator circuit**

the cathode follower, $T_5$, driving the flattener so that only the part of the pulse above the cut-off potential of the triode is used.

A cathode follower stage is used as an output stage for the pulse shaper so that the output impedance may be low.

### Z-axis Pulse Generator

It is necessary to apply a square pulse to the intensity grid of the cathode ray gun at a time when the pulse on the horizontal deflection plates of the gun is at its maximum. This is done by a triggered pulse generator shown in Fig. 6. The trigger pulse is obtained by delaying the pulse to be analyzed with a delay line, $D_1$ so that the trigger pulse (d) will have its leading edge at the maximum of the applied pulse. This positive signal is used to fire the 2D21 thyratron, $T_2$, of the pulse generator. The thyratron will stay fired until the signal reflects from the open-ended transmission line, $L_1$, connected to the plate of the thyratron. This negative pulse extinguishes the thyratron. A square pulse of voltage will, therefore, appear across the resistor (f) in the cathode of the thyratron. This square pulse has a leading edge at the point at which the applied pulse reaches a maximum and a width of 5 $\mu$sec, which is twice the delay time of the delay line.

### Deflection Amplifier and Bias System

The electron gun is sensitive in deflection sensitivity to the anode voltage. The spot diameter of the electron beam is smaller and the magnetic deflection is less with high anode voltages, so a 3000-volt regulated power supply is used to supply the anode voltage for the electron gun.

At this anode voltage the deflection sensitivity is such that the electron gun requires a horizontal pulse deflection voltage of about 1000 volts. The pulse

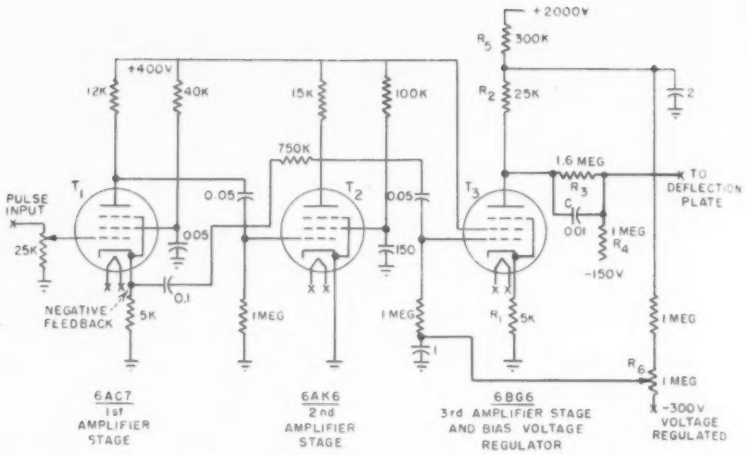



**FIG. 7. Deflection amplifier and bias system**

to be analyzed is amplified to this voltage by the deflection amplifier shown in Fig. 7.

The pulse from the pulse shaper is amplified by a pair of pentode, *RC*-coupled amplifiers, $T_1$ and $T_2$. These amplifiers have negative feedback to stabilize their gain.

The output amplifier is a 6BG6 beam power pentode. Cathode resistor, $R_1$, provides negative feedback for gain stabilization and increased linearity. The output pulse appears across $R_2$ in the plate circuit of $T_3$. The d-c potential of the plate of $T_3$ is divided by $R_3$ and $R_4$ so that the d-c bias of the deflection plate connected to them (with respect to −150 volts) is proportional to the plate voltage. This plate voltage is regulated at a constant d-c potential by negative d-c feedback to the grid of $T_3$. This potential may be adjusted to any desired voltage, to give the desired deflection plate bias, by varying $R_6$. To reduce the current drain on the 2000-volt power supply for the tube and still provide a low pulse output load resistance $R_2$, an additional bypassed plate-dropping resistor $R_5$ is inserted in the plate circuit.

The entire pulse output voltage is coupled to the deflection plate by $C_1$. By applying the entire pulse voltage and only a portion of the d-c voltage of the plate of $T_3$ to the deflection plate, the pulse on the deflection plate can be made to go negative with respect to ground from a positive d-c bias. The beam of the cathode ray gun can, therefore, be deflected from its reference point on one side of the screen to the other side by a large pulse. By use of this system of bias, both horizontal deflection plates will be at zero potential when the beam is in the center of the screen. This system of bias has less astigmatism of the beam than a bias system which uses one deflection plate for the applied pulse and the other plate for the d-c bias to set the reference position of the beam.

### Output Amplifiers

The amplifier which increases the current from the collecting anodes of the pulse analyzer tube to a current large

enough to operate a mechanical register must pass several rather stringent requirements. It must be simple and require only a few tubes, since fifty such amplifiers must be built. A complex circuit would be expensive and require more frequent repair. The amplifier must reliably amplify pulses of 0.3 $\mu$a with a pulse width of less than 5 $\mu$sec to a current of several hundred milliamperes of a duration of several milliseconds. This can be done with the three-tube amplifier shown in Fig. 8.

The input, $T_a$, is a cathode follower which has a low capacitance input impedance of about 0.5 megohms. The shield, $S_1$, of the input cable inside the grounded shield, $S_2$, is connected to the cathode of the 6J6 to reduce the effective capacitance of the input cable and still provide a method of shielding the input. The other section $T_b$ of the input tube is used as a grounded-grid, cathode-coupled amplifier. The difference in potential between grid and cathode is provided by changing the cathode potential of the second section, $T_b$, of the first tube and keeping the grid voltage constant.

This type of amplifier has the advantages of giving a high gain with a high input impedance. It has the output in phase with the input, and broadens the pulse so that it can be amplified better in the next stage. The grounded-grid stage has electrostatic shielding between the input and the plate, and since the output pulse is negative, a high plate resistor may be used, giving a high gain without much loss in pulse height due to output capacitance.

The next stage is a conventional pentode *RC*-coupled amplifier using a type 6AU6 with zero grid bias.

The 6J6 and 6AU6 amplify the 0.3 $\mu$a pulse of less than 5 $\mu$sec width to a 60-volt pulse of about 10 $\mu$sec width. This is quite sufficient for firing a thyratron such as a 2D21 or 2050 which will operate the mechanical register which will then count the number of pulses of current on collecting anode $A_1$.

The sensitivity of the amplifier may be changed by changing the bias of the output thyratron with $R_2$.

The sensitivity is adjusted so that the mechanical register will trip if more than half of the beam is striking the collector anode to which it is connected. By doing this, the definition of the pulse

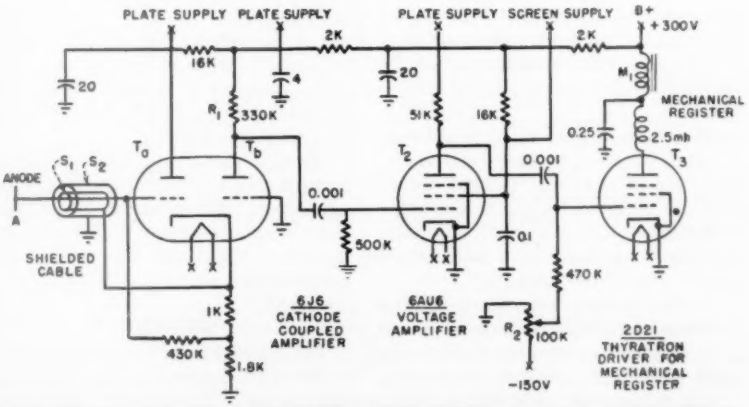



**FIG. 8. Circuit of the output amplifier which drives the mechanical registers**

analyzer may be increased, since, if the beam strikes the edge of an anode, it will trip the register of the anode that most of the beam is striking.

### Construction of the Tube

The general idea of the pulse analyzer tube may be gathered from Fig. 1. The chamber is made of brass with a lucite end plate. Fuse wire gaskets are used for all metal joints, and a plastic gasket is used for the end plate.

A standard 11-pin female socket is mounted on a plate on the small end of the chamber. The wires are fed through this plate so that a standard cathode ray tube electron gun can be mounted in the socket without any change in base pin connections.

The electron gun from a 3GP1 or 5LP1 cathode ray tube may be used. The glass envelope of the electron gun is cracked with a hot wire and broken off near the base of the tube, leaving the electron gun supported on the tube base.

At first the guns were taken apart and the cathode recoated with a commercial oxide cathode coating. This proved to be unreliable in giving a well-focused electron beam. It was found that the cathode of the electron gun could be reactivated without recoating it by heating it in about $10^{-4}$ mm Hg of hydrogen. This gave quite a satisfactory focus. The cathode could be exposed to air and reactivated several times.

The electron gun operates satisfactorily at a pressure of $10^{-3}$ mm Hg or less. To provide this vacuum, an oil diffusion pump with a pumping speed of 100 liters per minute is used. The tube is usually operated at a pressure of approximately $10^{-5}$ mm Hg.

A thermocouple ion gage is used to measure the chamber pressure above $10^{-3}$ mm and an electronic triode ion gage is used for pressures below this.

The lucite end plate has a 3-inch fluorescent screen and a series of 50

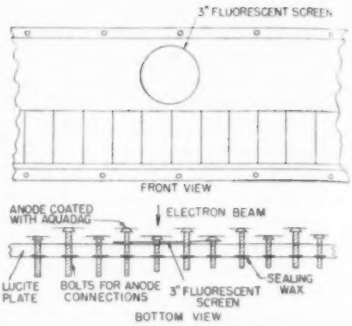



**FIG. 9. Arrangement of anodes as placed in the end of the analyzer tube**

anodes mounted on it. The beam can be focused visually on the fluorescent screen. A 3-inch cathode ray tube is connected in parallel with the pulse analyzer tube to use as a pilot for setting the position of the beam in the master tube.

The anodes are mounted as shown in Fig. 9. They are staggered to reduce the capacitance between adjacent plates and to eliminate the gap in the horizontal direction between adjacent anodes. The anodes are made of sheet copper and are coated with aquadag to reduce secondary emission. The anodes are soldered to brass bolts which extend through the lucite end plate and are sealed in with sealing wax.

The chamber is mounted on a steel framework and is shielded magnetically by a sheet iron housing.

After this model was tested, a similar, much smaller tube was constructed with a sealed-off glass envelope. This tube has 48 anodes across a 3-in. anode structure. Its beam current is approximately 4 $\mu$a.

### Applications

The pulse analyzer works satisfactorily, the definition and stability being quite good. At present the pulse repetition rate is limited to about 35

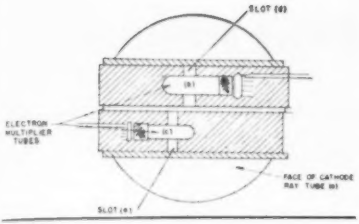



**FIG. 10. Photoelectric cell system**

μsec separation if the adjacent pulses are of different height so they operate different registers. (A single mechanical register has a repetition rate of only about 120 pulses per second.) The instrument could be made to have a pulse repetition rate limited only by the ionization chamber and mechanical register speeds.

A system has been constructed, as shown in Fig. 10, in which an ordinary cathode ray tube is used instead of the pulse analyzer tube, and 931-A multiplier tubes (b) and (c) are used, instead of anodes, to detect the position of the beam. This system has only two channels and is used for short half-life determination.

The position at which the pulses are detected is adjusted by varying the position of the slots (d) and (e) in front of tubes (b) and (c). The width of the channel can be adjusted by varying the width of the slots (d) and (e). An r-f signal is applied to the vertical deflection plates to spread the spot in the vertical direction so that it may be detected by either tube. The 931-A tubes give a pulse output of approximately 5 volts when a pulse of light appears on the fluorescent screen.

For measuring short half-lives of certain isotopes one slot (d) is set at the energy of an isotope emitting an alpha particle, and the other slot (e) is set at the alpha energy of the daughter product. An isotope will decay by emitting an alpha particle to another isotope, which will emit another alpha particle. The time between these two alpha particles is a measure of the half-life of the second isotope.

The pulse analyzer tube may be used as a device for measuring the time between these two pulses. A linear-triggered sweep may be tripped by the first alpha particle pulse so that the beam of the cathode ray gun will sweep at a constant rate from one end of the series of anodes to the other. The beam, which is normally off, can then be turned on by the second alpha particle pulse. The beam will then be turned on at an anode corresponding to the time between the two pulses. A plot of the counts appearing on the mechanical registers connected to these anodes will give a plot of the number of counts vs. the time between pulses. This is an exponential and corresponds to the exponential decay of the second alpha emitter. From this curve the half-life of the isotope can be calculated.

* * *

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## ERRATA: "Cosmic Rays—I"

J. M. Jauch has recently issued the following errata to his paper entitled "Cosmic Rays—I" (NUCLEONICS, pp. 39–51, April, 1949):

*P. 40, 1st col., 25th line:* Sentence should read "It produces on sea level an ionization of about 1–2 ion pairs per $cm^3$ and per second."

*P. 48:* Eq. 16 should read

$$l = \frac{137}{4}\left(\frac{mc^3}{e^2}\right)^2 \frac{1}{NZ^2} \frac{1}{\ln\,(183/Z^{1/3})}$$

# Bibliography on Radiation Protection

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THIS BIBLIOGRAPHY, like the previous one on radiation detection [NUCLEONICS 4, No. 5, 142 (1949)], was compiled in response to a request from the Nuclear Studies Committee of the Institute of Radio Engineers. Both bibliographies will appear as part of a report to be issued under the auspices of the Committee on Nuclear Science of the National Research Council. A more comprehensive bibliography on this subject is being compiled by the author for the United Nations ("An International Bibliography on Atomic Energy," Vol. II—Scientific Aspects).

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*Specific heat of $C_7F_{14}$.* H. S. Arms, 12/42. BDDA 128

*Uranyl nitrate.* BDDA 129

*Report on the electrolysis of used U-chlorides for metal production.* Drs. Stacey and Wilkinson, 9/41. BDDA 130

*Determination of vapor pressure of $UF_6$ between 20 and 30° C.* C. B. Amphlett, L. F. Thomas, 8/41. BDDA 131

*Determination of the vapor density of U-hexafluoride at 30° C.* C. B. Amphlett, L. F. Thomas, 9/41. BDDA 132

*Report on the reconversion of hexafluoride to metal. Part I. Conversion of U-hexafluoride to $U_3O_8$.* C. B. Amphlett, L. F. Thomas, 10/41. BDDA 133

*The vapor pressure of heavy water.* W. A. Bell, 5/42. BDDA 134

*The total neutron collision areas of some heavy metals.* E. Bretscher, E. B. M. Murrell, 1/43. BDDA 135

*The production of 9 kg of sulphur hexafluoride.* A. M. Dawson, A. J. Lowe, 3/42. BDDA 136

*Tables of capture cross section for thermal neutrons.* L. Kowarski, 3/42. BDDA 137

*Construction of G-M Counters.* N. Veall, 12/42. BDDA 138

*A flowmeter for small gasflows.* A. F. Brown, 1/43. BDDA 139

*The production of $UCl_4$ from $U_3O_8$.* Drs. Stacey and Wilkinson, 2/42. BDDA 140

*On the preparation of organic fluoro-derivatives.* W. K. R. Musgrave, H. G. Bray, 2/42. BDDA 141

*Pressure-density relationship for $UF_6$.* L. F. Thomas, 3/42. BDDA 142

*Organic fluorides.* Dr. F. Smith, 5/42. BDDA 143

*Investigation of the pressure-density relationship for U-hexafluoride.* L. F. Thomas, 5/42. BDDA 144

*Deuterium exchange reactions.* H. E. Eduljee, 4/43. BDDA 145

*Orifice plate calibrations. Report No.* 1. G. A. R. Hartley, R. W. Morton, 5/43. BDDA 146

*Empirical formulae for the boiling points of the fluorocarbons.* H. A. Skinner, 5/43. BDDA 147

*The action of HF upon halogenated (chloro) hydrocarbons. Direct replacement of Cl by F.* Dr. F. Smith, Mr. W. K. R. Musgrave, 4/43. BDDA 148

*Preparation of benzotrifluoride.* J. Chapman, W. B. Whalley, 9/43. BDDA 149

*Separation of hydrogen-carbon dioxide mixture by the centrifugal action of a jet.* J. A. V. Fairbrother, 9/43. BDDA 150

*Sensitivity of a fast neutron counter for a near source.* N. Feather, 12/42. BDDA 151

*The chemical and physical properties of the fluorocarbons.* A. J. Rudge, N. F. Sarsfield, 10/43. BDDA 152

*An attempt to forecast some physical constants for selected fluorocarbons.* A. J. Rudge, 11/43. BDDA 153

*Fluorotoluenes. Part I. Experiments on the preparation of benzotrifluoride.* J. Chapman, W. B. Whalley, 11/43. BDDA 154

*The elementary fluorides and their use as fluorinating agents—a general review* (June 1943). N. F. Sarsfield, H. A. Skinner, 12/43. BDDA 155

*Fluorotoluenes. Part II. Nuclear fluorinated toluenes.* C. W. Suckling, 2/44. BDDA 156

*Fluorotoluenes. Part 3. Nuclear fluorinated benzotrifluorides.* C. W. Suckling, W. B. Whalley, 2/44. BDDA 157

*Notes on the production of fluorocarbons and related compounds at Weston Point.* A. J. Rudge, 5/44. BDDA 158

*Radiative capture of spontaneous fission neutrons in spheres of different size.* N. Feather, 4/48. BDDA 159.

*The ultra-violet absorption spectra of some fluorinated hydrocarbons.* Miss D. Grove, 9/44. BDDA 160

*Addendum to Report No. Br.* 315 (*BDDA* 114). *Further remarks on the correction for self-absorption in β-ray measurements.* N. Feather, 9/44. BDDA 161

*The refining of fluorocarbons, January 1943–March* 1944. N. F. Sarsfield, 11/44. BDDA 162

*Vacuum testing. The spectroscopic method of leak detection.* A. H. Turnbull, R. Lipscomb, 2/45. BDDA 163

*Fluorokerosene—production by the vapor phase $CoF_3$ process. Part I. Laboratory scale work.* A. M. Dawson, 6/45. BDDA 164

*Preliminary report on the number of neutrons emitted by a beryllium-radium photosource.* E. Gluckauf, 12/45. BDDA 165

*Fluorocarbons—Physical properties and composition. Part 5. Refractivity and*

*density-revision of standard factors.* N. F. Sarsfield, 2/46. BDDA 166

*Fluorocarbons—Physical properties and composition. Part 3. Boiling points.* N. F. Sarsfield, 2/46. BDDA 167

*Fluorokerosene by the vapor phase $CoF_2$ process. Part 2. Semitechnical work.* D. F. Barratt, 2/46. BDDA 168

*Fluorocarbons—Physical properties and composition. Part 4. Molecular weights.* N. F. Sarsfield, 2/46. BDDA 169

*Fluorocarbons—Physical properties and composition. Part 2. Refractivity and density-compounds of C, F, H and Cl.* N. F. Sarsfield, 3/46. BDDA 170

*Trichloroacetyl peroxide. Investigation of preparation and stability.* J. T. McCombie, 5/47. BDDA 171

*Fluorolubes from freon-113. A digest of U. S. reports on the Miller process.* N. F. Sarsfield, 2/45. BDDA 172

*Specific refraction of $CF_2 = CFCl$ polymers.* N. F. Sarsfield, 6/45. BDDA 173

*Preparation of lubes by polymerization of trifluorochloroethylene.* R. G. R. Bacon, 5/47. BDDA 174

*Effect of packing on critical size.* K. Fuchs. BDDA 175

*Effect of packing on the critical radius of the sphere.* K. Fuchs. BDDA 176

# BOOKS

THE SCIENCE AND ENGINEERING OF NUCLEAR POWER, edited by Clark Goodman, published by Addison-Wesley Press, Cambridge, Mass.; Vol. I, 501+ pages, $7.50 (1947); Vol. II, 344 pages, $7.50 (1949). *Reviewed by Irving Kaplan, Brookhaven National Laboratory.*

It is unfortunate that the peacetime development of nuclear power has been retarded because of political and military considerations. In contrast to the free and wide-spread development which in the past characterized great scientific advances, research and development in the field of nuclear power are limited to a relatively small number of restricted laboratories. Most universities and industries have neither the trained personnel nor the information with which to pursue work in this field. It is inevitable that progress will be delayed by limitations on the free exchange of ideas and information.

The volumes under consideration represent, to the best of this reviewer's knowledge, the first attempt to treat openly and systematically the problems of nuclear power. In view of the limitations set on the one hand by the secrecy required by law and on the other hand by the primitive state of the field, it is impossible to prepare and publish a unified and thorough treatise on nuclear power. Because of these limitations, this book cannot be regarded as such a treatise. It consists essentially of the material of a series of seminars on the problems of chain reacting systems conducted at the Massachusetts Institute of Technology since the Fall of 1946 and, as such, constitutes a valuable addition to the published literature on nuclear energy.

The first volume, published in 1947 is a general survey of the fundamentals of chain-reacting systems and treats such subjects as: Fundamentals of Nuclear Physics, The Physics and Chemistry of the Fission Process, Elementary Reactor Theory, the Construction, Control and Operation of a Nuclear Reactor, and Nuclear Fuels.

The second volume, published more recently, is primarily a supplement to the first volume and treats specific problems in some detail. It contains seventeen chapters, each dealing with a different subject and written by a different author. Among the subjects treated are: Source Materials for Nuclear Power, Isotope Separation, Theo-

retical Basis of Some Measurements Useful in Pile Design, Calculation of Neutron Distribution in Heterogeneous Piles, Pile Kinetics, Heat Removal from Nuclear Reactors, Shielding of Nuclear Reactors, Effects of Radiation on Materials, Pile Materials, Production of Radionuclides, Health Physics, and Future Developments in Nuclear Energy.

The treatment is, for the most part, elementary and is aimed at the nonspecialist. However, the authors of the various chapters are all specialists who have contributed significantly to progress in the field of nuclear energy, and the material is authoritative as far as it goes. The emphasis throughout is on the basic theory and experimental background underlying the many problems that face workers in the field. One of the chief virtues of the book is the collection in a useful form of discussions of the various aspects of nuclear energy. This usefulness is enhanced by the many well-executed tables, charts and figures.

The two volumes together offer a well-rounded introduction to the field of nuclear energy; they should be valuable to the nonspecialist, who is interested in the general aspects of nuclear energy and to the potential worker in a special field who wishes to acquaint himself with the many problems in that field.

To the specialist, the book offers a convenient source of information on particular phases of nuclear science and engineering other than his own. This is especially important in view of the close cooperation which is required in this field between physicists, chemists, engineers, and health physicists. The effectiveness of this cooperation depends to a large extent on the degree of mutual understanding which exists between specialists in these different branches of science, and these MIT volumes have already proved their usefulness in this respect. For example, although the chapters on Heat Transfer and Heat Removal from Nuclear Reactors may appear elementary to the engineer, they should help the physicist, chemist, and metallurgist to understand the engineering problems involved in nuclear reactors. Many other instances of this kind could be cited.

It is to be hoped that as advances are made in nuclear energy further volumes will appear which will go more deeply into the subject, and in which a more consistent and unified treatment may be possible. It would be helpful, for example, if the theory of neutron diffusion and transport were treated more fully, and if a more extensive bibliography were available than that offered by the present volumes. It is, I think, unfortunate that relatively little reference is made to the published literature especially in cases where more detailed treatments of particular subjects are available, such as the U. S. Atomic Energy Commission declassified documents. These, however, are minor shortcomings.

Professor Goodman and his colleagues at MIT are to be congratulated for having, by these volumes, set an example which, if followed at other universities, will do much to stimulate the further development of nuclear energy and help supply the basic training and personnel needed in this field.

(EDITOR'S NOTE: It was recently announced that "The Science and Engineering of Nuclear Power" will be published annually. Volume III is expected to be available sometime after January, 1950.)

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ON THE THEORY OF STOCHASTIC PROCESSES AND THEIR APPLICATION TO THE THEORY OF COSMIC RADIATION, by Niels Arley, John Wiley and Sons, Inc., New York, first American edition, 1948, 240 pages. $5.00. *Reviewed by*

*J. M. Jauch, Assoc. Prof. of Theoretical Physics, State University of Iowa.*

The theory of stochastic or random processes has found an ever-increasing range of applications in various, quite unrelated, branches of the physical sciences. In modern atomic physics especially, the approach of the elementary units of matter with a rapidly progressing experimental technique has revealed the two outstanding facts that elementary particles can be annihilated, created, and transformed into each other and that these transformation processes are governed by probability laws. The most impressive examples of such transformation processes are furnished by the showers observed in the soft component of cosmic radiation. Calculating the evolution of a shower when a primary photon or electron enters an absorber has been the subject of much theoretical research in the past. All attempts to calculate the probability of finding a given number of particles under a certain absorber thickness have so far failed. Chance of success is bettered if the exact equations of the shower theory are replaced by a suitably chosen model that exhibits the main characteristics of the real transformation processes but is sufficiently simple to be treated with analytical methods.

It is fortunate that Niels Arley, who has made notable contributions to this approach of the shower theory (some of which are accessible only in Danish), has written a book which presents a very clearly written introduction to the mathematical apparatus of the modern theory of random processes and a detailed account of the applications of this theory to the shower theory of cosmic rays.

The book is divided into three parts. Part I contains the mathematical theory. It treats the general theory of discontinuous stochastic processes in the one- and multidimensional case.

In Part II the application of theory in cosmic-ray problems is discussed. The gaussian and the Furry model are supplemented with a third, the Pólya model, which depends on two independent parameters and contains the two previous models as special cases. The usefulness of the Pólya model for the problems in shower theory stems from the fact that the first and second moment of the probability distribution can be adjusted separately by choosing the two parameters suitably.

Part III contains two further mathematical chapters that supplement the contents of Part 1.

The comparison of the theoretical shower curves with the experimental value is only fair in some of the cases cited. It is not easy to interpret the remaining discrepancy in view of the many approximations involved in obtaining the final theoretical result. In the first place, the probabilities for the elementary processes are only approximate expressions. Furthermore the effect of the energy loss by ionization is included only by the assumption that above the critical energy $E_c$ for which ionization loss and radiation loss are equal, the electrons undergo multiplication; below this energy they are absorbed without multiplication. Finally the energy spectrum of the soft component which enters into the final results is only approximately known. All these errors combine with the errors introduced by the mathematical approximations and it seems very difficult to separate them in the final results. To this must be added that the geometrical conditions of the various experimental arrangements are sometimes far from simple and the systematic errors of a particular experiment are very difficult to estimate.

The author concludes that the experimental material so far available favors the Pólya distribution but that further experiments are still highly desirable.

# NUCLEONIC EVENTS

## DEAN AND SMYTH APPOINTED TO AEC

The Senate has confirmed President Truman's nominations of Gordon Evans Dean, professor of law at the University of Southern California, and Henry DeWolf Smyth, chairman of the department of physics at Princeton University, to fill two vacancies in the United States Atomic Energy Commission.

The newly-filled posts were vacated by William W. Waymack, who resigned as commission member in December, and by Robert F. Bacher, who resigned early in May to accept a position at the California Institute of Technology as director of the Norman Bridge Laboratory of Physics and chairman of the departments of physics, mathematics, and astrophysics.

Smyth, author of "Atomic Energy for Military Purposes" which became known as the famous "Smyth Report," is fifty years old. As a scientist, he would replace Bacher on the commission. Born in Clinton, New York, Smyth prepared early to study physics at Princeton, where his father was a professor of geology. The degrees he took there included a B.A., M.A., and Ph.D. Cambridge University awarded him another doctorate in 1923 after he had worked as a National Research Council fellow. He joined the Princeton faculty in 1924. In 1940 he was drafted for war work at Princeton for the NRC and OSRD and in 1941 directed projects concerned with chain reactions and isotope separation. From 1943 until the end of the war, he was a consultant for the Manhattan Project and directed the work of its metallurgical laboratory in Chicago.

Dean, who was born in Seattle, Washington, is forty-three. He has a B.A. from the University of Redlands, a J.D. from the University of Southern California law school, and a LL.M. from Duke University. California admitted him to the bar in 1930 and North Carolina in 1931; in 1935 he was admitted to practice before the United States Supreme Court. Work with the Department of Justice in 1934–36 led to his appointment soon after as a special executive assistant to the U. S. Attorney General. In 1945 he became an assistant to Justice Robert Jackson at the Nuremberg trials and for his work in this capacity was awarded the Medal of Freedom in 1946.

## IRE FORMS PROFESSIONAL NUCLEAR SCIENCE GROUP

A professional group in the field of nuclear science has been formed by the Institute of Radio Engineers. Its activation was the result of interest shown in this field by members of the IRE and was an outgrowth of the activities of the IRE's Nuclear Studies Committee under the chairmanship of L. R. Hafstad, head of the AEC's Reactor Division.

The new group will operate within the framework of the IRE, serving the interests of those members participating or interested in the field of nuclear science. Constitution and bylaws are now being drawn up for the new organization and announcement of its plans for future activities is expected in the near future.

At its first organizational meeting, the new group chose as chairman Harner Selvidge, director of special products development of Bendix Aviation Corp., Detroit, Mich. There are no fees or dues, membership in the IRE being the only prerequisite for membership in the new group. Additional information can be obtained from Dr. Selvidge or IRE headquarters in New York.

## URANIUM PROCESSING PLANT TO BE SET IN OPERATION

The Atomic Energy Commission has signed a contract with the U. S. Vanadium Corporation for the rehabilitation and operation of the company's uranium-vanadium processing plant at Uravan, Colorado. Under the terms of the contract, the company has agreed to rehabilitate the plant and the company-owned townsite and install new equipment and facilities for the recovery of uranium. The AEC has agreed to purchase the mineral production of the plant at a guaranteed unit price until June 30, 1954.

The Uravan plant is expected to be ready for operation about the end of this year.

The signing of this contract completes arrangements for the operation of all five of the existing uranium-vanadium ore-processing plants in the Colorado Plateau area. The other four plants are at Naturita, Rifle and Durango, Colorado, and Monticello, Idaho.

## AEC LISTS CONSULTANTS ON ISOTOPE TECHNIQUES

The Isotopes Division of the Atomic Energy Commission has issued a list (below) of names of men who have expressed willingness to serve as consultants on isotope techniques to isotope users outside AEC facilities.

Although each of the men who appears in this compilation has consented to have his name included, the time that any one individual will have for consultation service will be necessarily limited by the demands of his regular work. All arrangements for services of this sort and for the consultation fees are to be made directly with the desired consultant.

The list consists primarily of physicists, but some radiochemists and radiobiologists are also included. It is a preliminary list, to answer the frequent requests concerning consultation. The Isotopes Division plans to expand it with additional names of physicists, chemists and biologists.

### CALIFORNIA

Arthur Adamson, Department of Chemistry, University of Southern California, Los Angeles

Luis W. Alvarez, Department of Physics, University of California, Berkeley

John Backus, Department of Physics, University of Southern California, Los Angeles

Melvin Calvin (chemist), Radiation Laboratory, University of California, Berkeley

Norman Davidson, Gates & Grellin Laboratories of Chemistry, California Institute of Technology, Pasadena

A. Theodore Forrester, Department of Physics, University of Southern California, Los Angeles

C. S. Garner, Department of Chemistry, University of California, Los Angeles

Myron B. Hawkins (engineer), Microchemical Specialties Co., 1834 University Avenue, Berkeley

A. C. Helmholz, Department of Physics, University of California, Berkeley

Geoffrey Keighley, Department of Biology, California Institute of Technology, Pasadena

Tom Lauritsen, Department of Physics, California Institute of Technology, Pasadena

K. R. MacKenzie, Department of Physics, University of California, Los Angeles

W. G. McMillan, Jr., Department of Chemistry, University of California, Los Angeles

William Parkins, Department of Physics, University of Southern California, Los Angeles

I. Perlman, Radiation Laboratory, University of California, Berkeley

J. R. Richardson, Department of Physics, University of California, Los Angeles

L. I. Schiff, Department of Physics, Stanford University, Stanford

Kenneth Scott (biologist), Radiation Laboratory, University of California, Berkeley

Hans Staub, Department of Physics, Stanford University, Stanford

B. M. Tolbert (chemist), Radiation Laboratory, University of California, Berkeley

Edward R. Tompkins, Microchemical Specialties Co., 1834 University Avenue, Berkeley

B. T. Wright, Department of Physics, University of California, Los Angeles

### CONNECTICUT

George M. Murphy, Sterling Chemistry Laboratory, Yale University, New Haven

E. C. Pollard, Sloan Physics Laboratory, Yale University, New Haven

### DISTRICT OF COLUMBIA

Don Loughridge, War Department, Pentagon Building, Washington, D. C.

### ILLINOIS

H. L. Anderson, Institute for Nuclear Studies, University of Chicago, Chicago

R. B. Duffield (chemist), Department of Physics, University of Illinois, Urbana

M. Goldhaber, Department of Physics, University of Illinois, Urbana

A. O. Hanson, Department of Physics, University of Illinois, Urbana

R. D. Hill, Department of Physics, University of Illinois, Urbana

W. F. Libby, Institute for Nuclear Studies, University of Chicago, Chicago

W. E. Meyerhof, Department of Physics, University of Illinois, Urbana

C. W. Sherwin, Department of Physics, University of Illinois, Urbana

Nathan Sugarman, Institute for Nuclear Studies, University of Chicago, Chicago

A. L. Turkevich, Institute for Nuclear Studies, University of Chicago, Chicago

P. Yankwich, Department of Chemistry, University of Illinois, Urbana

### INDIANA

E. J. Konopinski, Department of Physics, Indiana University, Bloomington

L. M. Langer, Department of Physics, Indiana University, Bloomington

K. Lark-Horovitz, Department of Physics, Purdue University, Lafayette

Allan C. G. Mitchell, Department of Physics, Indiana University, Bloomington

Milo B. Sampson, Department of Physics, Indiana University, Bloomington

Don Tendam, Department of Physics, Purdue University, Lafayette

Roger G. Wilkinson, Department of Physics, Indiana University, Bloomington

### MASSACHUSETTS

Sanborn C. Brown, Department of Physics, Massachusetts Institute of Technology, Cambridge

Martin Deutsch, Department of Physics, Massachusetts Institute of Technology, Cambridge

S. E. Eaton, Arthur D. Little, Inc., Cambridge

Robley D. Evans, Department of Physics, Massachusetts Institute of Technology, Cambridge

R. G. Fluharty, Department of Physics, Massachusetts Institute of Technology, Cambridge

John W. Irvine, Jr., Department of Chemistry, Massachusetts Institute of Technology, Cambridge

A. K. Solomon, Biophysical Laboratory, Harvard School of Medicine, Boston

### MICHIGAN

James M. Cork, Department of Physics, University of Michigan, Ann Arbor

Harry J. Gomberg, Department of Physics, University of Michigan, Ann Arbor

### MINNESOTA

Alfred O. C. Nier, Department of Physics University of Minnesota, Minneapolis

J. H. Williams, Department of Physics, University of Minnesota, Minneapolis

### MISSOURI

Martin D. Kamen (chemist), The Edward Mallinckrodt Institute of Radiology, Washington University, St. Louis

A. C. Wahl, Department of Chemistry, Washington University, St. Louis

### NEW JERSEY

Harry W. Fulbright, Palmer Physical Laboratory, Princeton University, Princeton

David L. Hill, Palmer Physical Laboratory, Princeton University, Princeton

Robert Hofstadter, Palmer Physical Laboratory, Princeton University, Princeton

Milton G. White, Palmer Physical Laboratory, Princeton University, Princeton

### NEW YORK

Sidney W. Barnes, Department of Physics, University of Rochester, Rochester

John DeWire, Laboratory of Nuclear Studies, Cornell University, Ithaca

R. W. Dodson, Department of Chemistry, Columbia University, New York

Carl L. Frederick, Frederic Flader, Inc., 583 Division Street, North Tonawanda

W. W. Havens, Department of Physics, Columbia University, New York

Ralph McCreary, Department of Physics, University of Rochester, Rochester

Joseph B. Platt, Department of Physics, University of Rochester, Rochester

Wendell C. Peacock, Sloan-Kettering Institute, 444 East 68th Street, New York

T. I. Taylor, Department of Radiochemistry, Columbia University, New York

John E. Vance, Department of Chemistry, New York University, New York

C. S. Wu, Department of Physics, Columbia University, New York

### NORTH CAROLINA

F. T. Rogers, Jr., Department of Physics, University of North Carolina, Chapel Hill

Marguerite M. Rogers, Department of Physics, University of North Carolina, Chapel Hill

**OHIO**

John E. Edwards, Department of Physics, Ohio University, Athens

H. R. Nelson, Battelle Memorial Institute, Columbus

M. L. Pool, Mendenhall Laboratory of Physics, Ohio State University, Columbus

J. D. Sayre, Ohio Agricultural Experiment Station, Wooster

**PENNSYLVANIA**

Jules Halpern, Department of Physics, University of Pennsylvania, Philadelphia

R. J. Maurer, Department of Physics, Carnegie Institute of Technology, Pittsburgh

**TEXAS**

Allen F. Reid, Department of Biophysics, Southwestern Medical College, Dallas

**WASHINGTON**

Joseph E. Henderson, Department of Physics, University of Washington, Seattle

Fred H. Schmidt, Department of Physics, University of Washington, Seattle

E. A. Uehling, Department of Physics, University of Washington, Seattle

## GENERAL ELECTRIC BUILDS 300-MEV SYNCHROTRON

The General Electric Research Laboratory is building a 300-Mev "nonferromagnetic synchrotron," according to C. G. Suits, vice president and director of research of the company. James L. Lawson is in charge of the design and construction of the device, which is being built under a contract with the Office of Naval Research and will be used for nuclear studies at GE.

The magnetic fields for the machine will be obtained from several sets of coils enclosed in a cylindrical tank, which is maintained at high vacuum. Thus, it is said, no separate glass doughnut will be needed.

## INT'L HARVESTER JOINS U. OF CHICAGO PROGRAM

The International Harvester Company recently became the eighteenth industrial organization to join the University of Chicago's industry-education atomic research program. The company has joined the Institute of Radiobiology and Biophysics. The Institute of Nuclear Studies and the Institute of Metals are the other two groups in the program.

E. I. du Pont de Nemours and Co. recently joined the Institute of Metals as the seventeenth member of the program.

## AEC SPONSORS 21 PROJECTS IN BIOLOGY AND MEDICINE

Twenty-one new research projects in biology and medicine will be financed by the Atomic Energy Commission under contract with 16 universities and two hospitals. Eleven of the contracts will be administered directly by the AEC through its operations offices. The remainder will be administered by the Office of Naval Research under the joint sponsorship research program announced last year.

The list below gives the name of the project, the project supervisor, and the contracting institution.

*Research in Radiobiology and Chemical Genetics.* H. H. Plough, Amherst College, Amherst, Mass.

*Studies on Chronic Beryllioisis, Tumor Production by Beryllium and Analytical Methods.* Robert Kehoe, University of Cincinnati, Cincinnati, Ohio.

*Use of Radioactive Iodine in Developing Quantitative Assay Method for Thyrotropic Hormone.* S. C. Werner, Columbia University, New York, N. Y.

*Comparison of the Effects of X-rays, Neutrons and Mustard Compounds on the Growth and Development of Corn Seedlings.* Mary A. Russell, University of Delaware, Newark, Del.

*The Physiologic and Pathologic Effects of Radioactive Cobalt.* Fred E. D'Amour, University of Denver, Denver, Colo.

*Metabolic Studies with Radioactive Isotopes.* Philip Handler, Duke University, Durham, N. C.

*Bioelectric Potentials of Plants and Animals as a Function of Radiation Injury.* A. A. Bless, University of Florida, Gainesville, Fla.

*Survival of Red Blood Cells after Treatment with Nitrogen Mustard.* F. W. Hartman, Henry Ford Hospital, Detroit, Mich.

*Proposed Investigation of Adsorption and Assimilation of Radioactive Waste by*

*Bacterial Slimes.* Abel Wolman, Johns Hopkins University, Baltimore, Md.

*Radium Chloride and Hemopoietic Physiology of Native Rodents.* E. R. Hall, University of Kansas, Lawrence, Kan.

*Treatment of Neoplasms.* Paul Hahn, Meharry Medical College, Nashville, Tenn.

*Radioautography.* Fred J. Hodges, University of Michigan, Ann Arbor, Mich.

*Measurement of Tissue Dose due to Gamma and Beta Active Radioisotopes.* R. Loevinger, Mount Sinai Hospital, New York, N. Y.

*Radioautographic Study of Beryllium-7.* C. T. Kaylor, C. P. Van Cleave, University of North Carolina, Chapel Hill, N. C.

*Metabolism of Copper.* J. A. Weybrew, North Carolina State College, Raleigh, N. C.

*Peanut Seed Irradiation.* W. C. Gregory, North Carolina State College, Raleigh, N. C.

*Movement of Ions through Soils Systems.* N. S. Hall, North Carolina State College, Raleigh, N. C.

*Use of Radioactive Isotopes in Studying Mold Metabolism, with Emphasis on the Assimilatory Mechanisms of Penicillium Chrysogenum.* Heinrich Koffler, P. A. Tetrault, Purdue University, Lafayette, Ind.

*Experiments to Determine the Feasibility of Developing Equipment that will be Capable of Mapping the Outlines of Organs or Deposits of Metastatic Tumor within the Body.* W. Scott, Washington University School of Medicine, St. Louis, Mo.

*Monomolecular Layers of Serological Agents.* E. C. Pollard, Yale University, New Haven, Conn.

*Irradiation of Viruses and Large Molecules.* E. C. Pollard, Yale University, New Haven, Conn.

## SUMMER MEETINGS and COURSES

### OAK RIDGE

A symposium consisting of thirty-two lectures on modern physics will be given at Oak Ridge from August 22 to September 2 under the joint sponsorship of the Oak Ridge National Laboratory and the Oak Ridge Institute of Nuclear Studies. The lecture staff will be drawn from among the physicists who are expected to spend the summer at the Oak Ridge National Laboratory. Lecturers probably will include: S. M. Dancoff, University of Illinois; J. G. Daunt, Ohio State University; Hubert M. James, University of Illinois; and Alvin M. Weinberg, Oak Ridge National Laboratory.

According to present plans, the lectures will include such topics as the current status of meson theory, the new quantum electrodynamics, recent progress in low temperature physics, classical nuclear physics, and declassified nuclear reactor theory. The lectures will be in the nature of a progress report to physicists in general rather than research reports to individuals within highly specialized fields.

In addition to the physics staffs at Oak Ridge, the lectures will be open without charge to physics department staff members and graduate students in physics in the South and elsewhere and interested individuals in related fields. The lecture series is being offered primarily for physicists from Southern universities but is open to others insofar as facilities permit.

Interested individuals should write the University Relations Division of the Oak Ridge Institute of Nuclear Studies, P. O. Box 117, for additional information.

* * *

The Special Training Division of the Oak Ridge Institute of Nuclear Studies announces that two basic courses in the techniques of using radioisotopes as tracers will be held during the balance of this summer. In addition, tentative plans are being made for a secondary course in instrumentation for radioisotope work.

The basic courses, similar to a series of seven offered at Oak Ridge last summer and during the fall and winter

months, will be given from July 11 to August 5, and from August 8 to September 2.

The secondary instrumentation courses will be of two weeks duration and will be open to research workers who have completed the basic course or its equivalent in actual radioisotope work. This course will be combined symposia and practical sessions on instrumentation. Tentatively scheduled for the period from September 5–16, it will be concerned with new developments in circuitry, scintillation counters and crystal counters.

Additional information on the courses and application forms may be obtained from Dr. Ralph T. Overman, Special Training Division, Oak Ridge Institute of Nuclear Studies, P. O. Box 117, Oak Ridge, Tenn.

### RENSSELAER POLYTECH

Joint Meeting, American Association of Physics Teachers and American Society for Engineering Education, Rensselaer Polytechnic Institute, Troy, New York, June 23 and 24.

### UNIVERSITY OF MICHIGAN

The University of Michigan's 1949 Summer Symposium on contemporary physics is scheduled to be held from June 27 to July 30. Guest lecturers will include Luis Alvarez of the University of California, R. P. Feynman of Cornell University, Frederick Seitz of Carnegie Institute of Technology, and G.B.B.M. Sutherland of Cambridge University. The program includes two or three lectures daily, with frequent colloquia on topics of current interest. No formal registration is required, and there are no fees for visitors having the doctoral degree. Further information may be obtained by addressing Dr. E. F. Barker, chairman of the department of physics, Ann Arbor, Michigan.

### UNIVERSITY OF CHICAGO

A course on the applications of chemistry to problems of geologic and cosmologic interest is to be given June 28–September 1 at the University of Chicago by Harold Urey and Harrison Brown. Selected topics relating the earth to the stars and to the planets of the solar system will be discussed. Special emphasis will be placed upon the chemical history of the earth's surface and atmosphere, geochronology, the development of the planets, and the origin and development of the life cycle. Specific applications of special chemical techniques will be discussed.

The course will be given Mondays, Wednesdays and Fridays at 11 a.m.

### BUREAU OF STANDARDS

The National Bureau of Standards has arranged two symposia on the effective utilization of automatic digital computing machinery to be held at the Bureau's Institute for Numerical Analysis in Los Angeles, Calif. The first symposium, to be held from June 24–25, will be on the construction and applications of conformal maps. The second, planned for June 27–29, will cover probability methods in numerical analysis.

Further information can be obtained from Dr. J. H. Curtiss, Institute for Numerical Analysis, Los Angeles 24, Calif.

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## *LITERATURE AVAILABLE*

**Prospecting for Uranium.** Published by the AEC and the U. S. Geological Survey, this 123-page, pocket-sized handbook provides information on the occurrence, identification and sale of uranium-bearing ores. The material contained in the booklet includes the names and characteristics of uranium-bearing ores, the types of deposits in which uranium occurs, the various tests that can be applied to identify uranium

minerals, techniques for using the Geiger counter, and the laws and regulations which affect uranium prospectors. *Available from Supt. of Documents, U. S. Govt. Printing Office, Washington 25, D. C., 30 cents. Lots of 100 are available at a 25% discount.*

**Medical X-ray Protection up to Two Million Volts.** Recommended standards of safety for the installation and use of high-voltage X-ray equipment are concisely set forth in this new 49-page handbook published by the National Bureau of Standards. The handbook was written by a subcommittee of the National Committee on Radiation Protection composed of representatives of radiological societies, electrical societies and the Bureau of Standards. *Available from Supt. of Documents, U. S. Govt. Printing Office, 15 cents.*

**Electronic Classifying, Cataloging and Counting Systems.** Prepared by Oak Ridge National Laboratory, this report includes descriptions of devices used in measuring the energy distribution of alpha particles. However, the report has applications to any field of observational science where the physical magnitude of the events under consideration can be electronically recorded. *Available from Office of Technical Services, Dept. of Commerce, Washington 25, D. C., 10 cents.*

**Radiation Instrument Catalog.** This catalog, compiled by the AEC Radiation Instrument Branch, gives descriptive information on the various instruments and accessories used in radioisotope work as well as the manufacturers producing the equipment. *Available from Document Sales Agency, P. O. Box 62, Oak Ridge, Tenn., 95 cents.*

**Industrial Uses of Radioactive Materials, A Selected Bibliography.** This 13-page bibliography, prepared by Arthur D. Little, Inc., covers the following: petroleum industry, mining and metallurgy, textiles, instruments, radiography, analysis, pharmaceutical research, glass, and radioisotope preparation. *Available from Arthur D. Little, Inc., Cambridge 42, Mass.*

**J.I.O.A. Subject Index: C.I.O.S. Volume I.** This is a new subject index and abstract collection of more than 1,000 unclassified scientific and technical reports prepared by the Combined Intelligence Objectives Subcommittee and dealing with European technology. Of interest to librarians and technical research workers, this 270-page publication of the Joint Chiefs of Staff is the first of a series of such volumes. They eventually will include reports of the British Intelligence Objectives Subcommittee (B.I.O.S.) and Field Intelligence Agency Technical (F.I.A.T.) as well as a group of minor reports, all dealing with the technical findings of Allied investigators in Germany and occupied Europe since the war. *Available from Office of Technical Services, Dept. of Commerce, Washington 25, D. C., $3.00 per copy. Orders should be accompanied by check or money order payable to the Treasurer of the U. S.*

**Isotopes and Their Application in the Field of Industrial Materials.** The 1948 Edgar Marburg Lecture (American Society for Testing Materials), as presented by Paul C. Aebersold, chief of AEC Isotopes Division, has been published in the form of a 28-page booklet. *Available from ASTM Headquarters, 1916 Race St., Philadelphia 3, Pa., $1.00.*

**Biological Applications of Nuclear Physics (BNL-C-4).** This is a 154-page report on a conference held at Brookhaven National Laboratory July 12–27, 1948. Twenty-four of the papers presented are reproduced. *Available from Information Group, Information and Publications Division, Brookhaven National Laboratory, Upton, N. Y., $1.50.*

**Isotopic Exchange Reactions and Chemical Kinetics (BNL-C-8).** This is a 239-page report on Chemistry Conference No. 2 held at Brookhaven National Laboratory December 1–3, 1948. It contains the complete contents of the 17 papers presented. *Available at address noted in previous item,* $1.00.

**Publications Available, Brookhaven National Laboratory.** A quarterly listing of publications issued by Brookhaven can be obtained from address noted in previous item.

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## NUCLEAR NEWSMAKERS

**James C. Stewart,** project engineer at the Oak Ridge National Laboratory, has been appointed manager of the AEC area office at Schenectady, N. Y., to succeed **Leonard E. Johnston,** who was recently named manager of the new reactor test station at Arco, Idaho. Mr. Stewart will represent the AEC in the management of the Knolls Atomic Power Laboratory, which is operated for the AEC by the General Electric Co.

**W. A. Bain,** assistant to the technical director of the Kellex Corp., has been promoted to the post of director of chemical research.

**Earle K. Plyler,** National Bureau of Standards physicist engaged in infrared research, has been appointed consultant to the AEC at Oak Ridge, where he will act in an advisory capacity on molecular spectra and infrared spectrometry.

**Rear Admiral John E. Gingrich** has resigned as director of the Security Division of the AEC. Admiral Gingrich has been recalled to active duty in the Navy, according to Carroll L. Wilson, AEC general manager. **Francis Hammack,** chief of the Personnel Security Branch of the Security Division, has been designated as acting director until a successor to Admiral Gingrich is appointed.

**John C. Franklin,** former vice president in charge of engineering for Trans-World Airline, has resigned as manager of the AEC's Office of Oak Ridge Operations. Mr. Franklin, who will continue to serve with the AEC as a consultant on technical and management matters, will return to private business.

**Albert G. Hill** and **Jerome B. Wiesner** have been appointed director and associate director, respectively, of the Research Laboratory of Electronics at the Massachusetts Institute of Technology, according to an announcement by James R. Killian, Jr., president of MIT. Prof. Hill, who had been associate director of the laboratory, succeeds **Julius A. Stratton,** who has been named provost of MIT. Prof. Wiesner was formerly assistant director.

**R. E. Lapp,** former executive director of the Committee on Atomic Energy of the Research and Development Board, has been appointed acting head of the Nuclear Physics Branch, Physical Sciences Division, Office of Naval Research.

**Eugene W. Scott,** assistant executive secretary of the Research and Development Board, has been appointed executive secretary of the Interdepartmental Committee on Scientific Research and Development, according to an announcement by **L. R. Hafstad,** chairman of the committee. Formed in 1947, the committee is responsible for the coordination of scientific research and development among federal agencies.

# PRODUCTS and MATERIALS

## GLOVED BOXES—BERKELEY TYPE

THE USE OF RADIOACTIVE MATERIALS in laboratories has introduced many problems, among the most serious being the control of contamination. To avoid the spread of radioactive materials and to facilitate decontamination, stainless steel fume hoods with high air capacity, benches with non-porous working surfaces, concealed piping, resistant walls, floors and ceilings, and special ventilating systems have been installed in many laboratories.

As an approach to a solution of the problem of contamination control, the Radiation Laboratory of the University of California undertook the development of "gloved boxes." These boxes, in their present form, are said to have virtually eliminated contamination beyond their interiors. **Scientific Service, Inc., 1834 University Ave., Berkeley 3, Calif.,** now offers these boxes as a commercial product.

Gloved boxes are being used for almost every type of laboratory operation and procedure, whether it be routine or exploratory. Since many procedures for radioisotope work are based upon microchemical techniques, essentially an entire laboratory can be placed in a single box. However, gloved boxes are not limited to micro-equipment since they are sufficiently large to accommodate much of the standard laboratory apparatus.

Since gloved boxes effectively limit the spread of contamination, thus reducing both health hazards and the possibility of cross-contaminating experimental material, they are useful for any operations that may result in the release of hazardous materials through spillage, volatilization, spattering, etc. Although these boxes were developed primarily for radioactive substances, with minor alterations they can be used for other hazardous materials such as bacteria, viruses, poisonous substances, *etc.* In addition, they are adaptable for almost any type of experimental work in a controlled atmosphere.

In addition to the problem of contamination, the handling of radioactive materials requires consideration of the radiation hazard. Surgical rubber gloves are capable of absorbing all alpha particles and essentially all beta particles in the energy range of those produced by $C^{14}$, $S^{35}$, *etc.* Consequently, the basic gloved box is designed

for work with curie amounts of such materials.

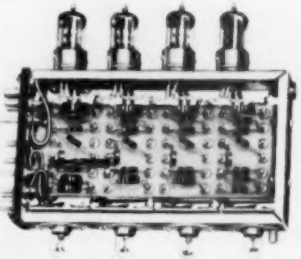
For protection against beta particles of higher energies and gamma photons of low energies, unit shields (close fitting shields of plastic, lead, steel, *etc.*) may be used around the individual containers of radioactive materials. By employing shields of this type, one hundred millicurie quantities of such radioisotopes may be handled safely with rubber gloves or with short tongs. In addition, lead glass windows can be placed over the standard window and special tongs can be operated through ball joints in the ports for handling larger quantities of gamma emitters. Special remote control equipment can be installed in the boxes for performing routine operations.

The spread of contamination from the gloved box is limited by the maintenance of a very slight negative pressure (about 0.1 inch of water) within the box. This vacuum is produced by a small centrifugal exhaust blower. While gaskets are used and/or close fits between parts are maintained, no attempt is made to construct an airtight box (except for controlled atmosphere work). The doors contain low-pressure-drop filters to allow a relatively high air flow (about 10 cfm) through the box. The exhaust air is filtered to remove dust particles and spray. In addition, special traps can be installed between the gloved box and the blower for removing corrosive vapors or radioactive gases. The air from the blower may be piped to a fume hood or to the outside of the building.

The box is constructed of plywood and is coated inside and out with white vinylbase paint of high resistivity. In addition, the interior is sprayed with a strippable coat to facilitate decontamination. The component parts fabricated of metals such as steel, duraluminum, brass, *etc.*, and located inside of the box, are coated with a chemically resistant, baked phenolic enamel. Parts subject to appreciable wear or abrasion which might damage the coating are made of stainless steel. Plastic parts are produced of materials selected for their chemical resistivity.

## COUNTER DECADES

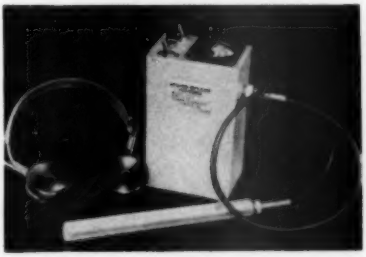
**Potter Instrument Co., Inc., 136-56 Roosevelt Ave., Flushing, N. Y.** The high speed electronic counter decades used in Potter instruments are now



available separately or in custom-designed equipment. The counting circuit features a direct decimal readout (0–9) on four neon glow lamps, which indicate directly the on-off condition of each of the four counter tubes. The plug-in decade utilizes four 12AU7 tubes and is designed for counting rates up to 130,000 per second.

## LIGHTWEIGHT COUNTER

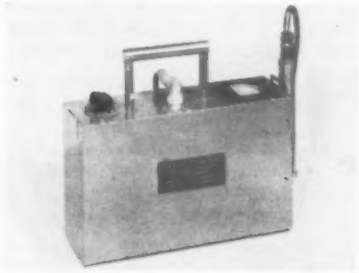
**Omaha Scientific Supply Co., 3623 Lake St., Omaha 4, Neb.** The TX-8 Geiger counter has been designed especially for



prospecting for radioactive minerals. Incorporating a rate meter, it is said to weigh less than four pounds and to have a battery life of at least six months.

### SURVEY METER

**Nucleonic Corp. of America, 497 Union St., Brooklyn 31, N. Y.** The model RM-1 radiation meter covers three



ranges of activity—5,000, 50,000 and 500,000 counts per minute. Used for alpha, beta, gamma and X-radiation, the instrument has a continuously variable high voltage supply (400–1,500 volts), which is obtained from 67.5-volt batteries.

### SURVEY METER

**Kelley-Koett Mfg. Co., Instrument Division, 212 W. Fourth St., Covington, Ky.** Unusual accuracy is claimed for

the model K-320 alpha-beta-gamma portable survey meter in the two ranges of 100 mr/hr and 1,000 mr/hr. Using a quartz-fiber electrometer construction, the meter incorporates a plastic window with an equivalent thickness of approximately 25 mg/cm² for beta measurements and a nylon window of approximately 2 mg/cm² equivalent thickness for alpha measurements.

### PROSPECTING COUNTER

**Precision Radiation Instruments, Inc., 1101 N. Paulina St., Chicago 22, Ill.** This 2-lb Geiger counter has been designed primarily for use in prospecting for radioactive ores. It employs a

900-volt plug-in type Geiger tube, which is contained in the case, with a 30 mg/cm² window. This is said to make possible the detection of beta particles with energies as low as 160 kev, as well as gamma rays. Using a crystal earphone, the instrument is 2¾ in. × 3¼ in. × 6 in.

### FLOW GEIGER TUBE

**Radiation Counter Laboratories, Inc., 1844 W. 21 St., Chicago 8, Ill.** The Mark 12 model 11 flow Geiger-Müller

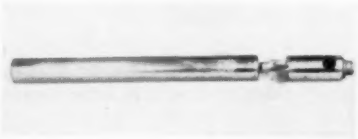
counter is a self-quenching detector for alpha, beta and gamma radiation which operates at about 1,350 volts. It is cylindrically shaped and has a 1⅛ in. diameter side window of 2.2 mg/cm² aluminum foil. The gas filling, supplied from a cylinder, is flowed slowly through the counter during operation.

## HELIUM CRYOSTAT

**Arthur D. Little, Inc., Cambridge 42, Mass.** The Collins Helium Cryostat is a device for liquefying helium and maintaining temperatures down to the liquid helium level (−452° F). It contains an experimental space 4 in. in diameter by 8 in. high, which can be held at any low temperature down to 2° Kelvin. For experiments outside this test compartment, an auxiliary coil serves to liquefy any gas, depending on the temperature level desired. The Cryostat without any auxiliary refrigeration, will liquefy helium at the rate of at least 1 liter/hr. The rate can be doubled by the use of liquid nitrogen in a special precooling coil. The equipment is 30 in. × 38½ in. × 55 in. tall and weighs about 1,200 lbs.

## COSMIC RAY COUNTERS

**N. Wood Counter Laboratory, 5646 Harper Ave., Chicago 37, Ill.** Cosmic



ray or gamma counters made of brass are available in 1, 1½ or 2 in. diameters, and 6 to 24 in. lengths.

## QUARTZWARE

**Panray Corp., 398 Broadway, New York, N. Y.,** is offering a complete line of standard laboratory ware made of transparent quartz for use wherever glass or pyrex has proved unsuitable. This quartzware is said to give long service in continuous use at extremely high temperatures, is chemically inert to almost all reagents (except HF), and is highly resistant to thermal shock.

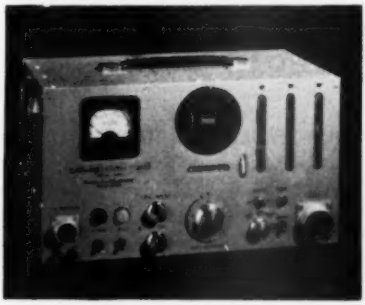
## POCKET ELECTROMETER

**General Electric Co., Specialty Division, Electronics Park, Syracuse, N. Y.** The model 4SN3A1 pocket chamber electrometer, employing a quartz fiber electrometer as the sensitive element,

is designed to read pocket pencil-type chambers carried by personnel working in areas where radioactivity exists. Radiation values are indicated directly on a conventional 3½-in. meter calibrated in mr. The unit, which weighs about 20 lbs, operates on two separate ranges, 0–50 and 0–250 mr, each with a separate scale on the meter.

## AUTOMATIC SCALER

**Berkeley Scientific Co., Sixth and Nevin Ave., Richmond, Calif.** The model



2000 Geiger-Müller scaler uses a decimal scale-of-1,000 and is said to be fully automatic. The decimal scale is used in combination with a direct-reading mechanical register with zero reset. The high voltage power supply is electronically regulated to 0.005% and is of the r-f type. The entire circuit is made up of seven plug-in units. Automatic operation for a predetermined number of counts up to 20,000 may be obtained.

## "PACKAGED" LABORATORIES

**Nuclear Instrument and Chemical Corp., 223 W. Erie St., Chicago 10, Ill.** Standard instruments have been grouped together into two basic "packaged" laboratories. They have been selected to provide complete facilities for routine counting or research work. Model L-165 includes a complete scaling unit, a thin mica end-window Geiger tube, a tube mount, and the necessary connecting cables and sample dishes for radiotracer research. Model L-163 (shown above) is designed for the analysis of radioactivity. It includes a complete automatic scaler, plus the Q-gas counter.

## PHOTOMULTIPLIER TUBE

**E. M. I. Research Laboratories, Ltd., Blyth Rd., Hayes, Middlesex, England.** The 5060 photomultiplier tube has the following specifications: photosensitivity—20–40 $\mu$a/L, multiplying stages—11, multiplication factor—$10^6$–$10^8$, interstage potential—160 v $\pm$ 5 v, safe max. collector current (d-c)—$10^{-3}$ amp, dark current—$\sim 10^{-8}$ amp, and capacitance of collector to all other electrodes—8 $\mu\mu$f. The company expects to restrict its future production to type 5311, which differs from the 5060 only in that it will have slightly increased dark current, caused by thermionic emission from the larger cathode.

## RADIOACTIVE MATERIALS

**Canadian Radium and Uranium Corp., 630 Fifth Ave., New York 20, N. Y.** The following materials are available: *radium*—American-mined and refined radium in containers to specifications; *polonium*—an alpha-ray emitter, supplied either on a metallic surface, or in solution as chloride or nitrate; *radium-beryllium neutron sources*—permanent neutron sources contained in brass or monel cylinders to specifications; *polonium-beryllium neutron sources*—gamma free, typical source contains approximately 10 mc of Po; *radiolead*—as nitrate, containing high concentration Ra D-E-F; *radium luminous compounds*—to demonstrate self-luminosity, can be used as weak gamma source in lecture demonstration; and *polonium luminous compounds*—gamma-free self-luminous material.

## ELECTRONIC COUNTER

**Streeter-Amet Co., 4101 N. Ravenswood Ave., Chicago 13, Ill.,** has developed a counter which can be actuated by any electrical pulse or signal from a contact switch, photo tube and amplifier, metal detector, *etc.* It is said that thay can be used in conjunction with Geiger counters and scaling circuits. The printing mechanism can be actuated in numerous ways (*e.g.*, a clock with fixed printing period can cause the printer to operate at one hour or 15 minute intervals).

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*June, 1949*

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NEUTRON WELL LOGGING

INTRODUCTION TO THE THEORY OF DIFFUSION AND SLOWING DOWN OF NEUTRONS—II

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Index to NUCLEONICS, Volume 4

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# *Sub-miniature in size*

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(Actual Size)

5803 5828

The 5803 electrometer triode is designed for use in portable ionization chamber instruments. Prime consideration is given to low grid currents, low filament power and low plate voltage. Filaments may be operated on A.C. or D.C.

TYPICAL OPERATION

| | | |
|---|---|---|
| Filament Voltage | 1.25 | v |
| Filament Current | 10 | ma |
| Plate Voltage | 7.5 | v |
| Grid Bias | −1.7 | v |
| Plate Current | 100 | ua |
| Transconductance | 100 | umho |
| Voltage Amplification | 2 | |

The 5828 medium mu triode is designed for use in portable Geiger Counter instruments as a D.C. or pulse amplifier requiring low filament current, low plate voltage, and high transconductance. To realize the usual long life of VX filaments, the duty cycle should be less than 50% when plate currents exceed 500 ua.

TYPICAL OPERATION

| | | |
|---|---|---|
| Filament Voltage | 1.25 | v |
| Filament Current | 10 | ma |
| Plate Voltage | 50 | v |
| Grid Bias | −0.5 | v |
| Plate Current | 600 | ua |
| Transconductance | 450 | umho |
| Voltage Amplification | 17 | |

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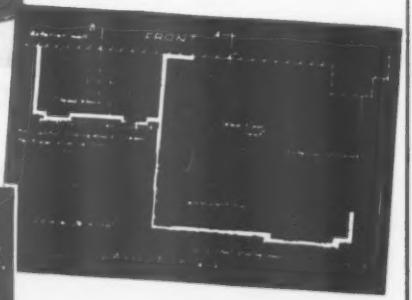


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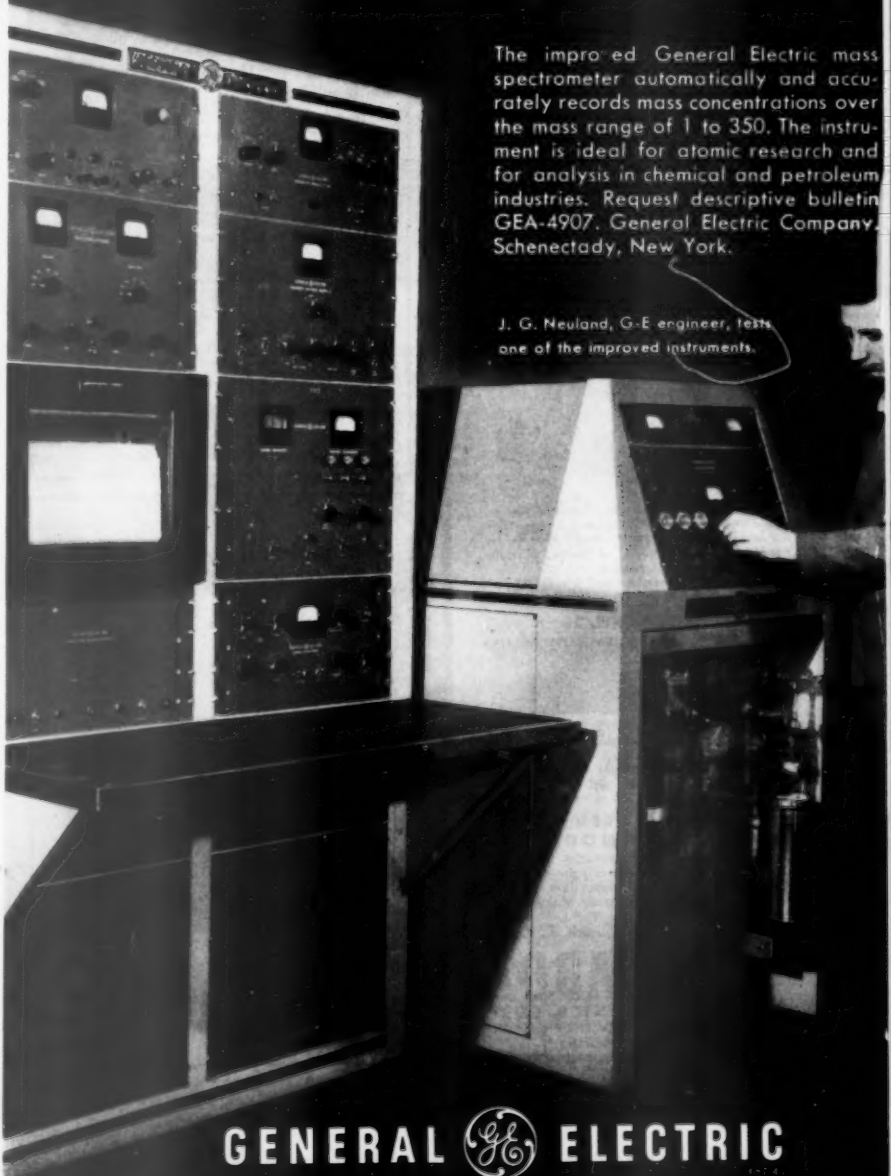
## *for direct recording over a wide range*



The impro ed General Electric mass spectrometer automatically and accurately records mass concentrations over the mass range of 1 to 350. The instrument is ideal for atomic research and for analysis in chemical and petroleum industries. Request descriptive bulletin GEA-4907. General Electric Company, Schenectady, New York.

J. G. Neuland, G-E engineer, tests one of the improved instruments.

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**BENCH MODEL 25**

Compact and light weight. Functionally designed for maximum convenience in operation. Six sturdy, insulated, "5-way" output terminal posts. Grey finish. 14" wide, 6" deep, 8" high. Weight 17 pounds.

**Model 25 Factory assembled and wired $39.95**
**Model 25K Complete kit 29.95**

**RACK MODEL 28**

Compact unit for standard rack mounting. Rear access terminal board. Panel 19"x5¼". Black wrinkle finish (grey optional). Depth behind panel 7½". Weight 16 pounds.

**Model 28 Factory assembled and wired $34.95**
**Model 28K Complete kit 24.95**

**BASIC REGULATED POWER SUPPLY KIT...MODEL 31K**

Basic kit of parts for incorporation into equipment. Comprises cased power transformer and filter choke, oil-filled capacitors, sockets, resistors, tubes and schematic diagram.

**Basic Kit 31K $14.95**

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Overall length — 3-3/8" Overall dia. — 1-5/16"

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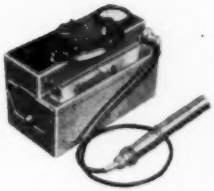

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Detects and measures very low intensities of Beta, Gamma and X-Rays. Differentiates between hard and soft rays. Meter dial calibrated directly in mr/hr., 0 to 20 mr/hr. Instrument is completely portable with GM tube mounted on 3 ft. probe. Low-drain amplifier assures long battery life. Desiccated case and probe. Earphones can be used.

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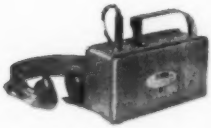

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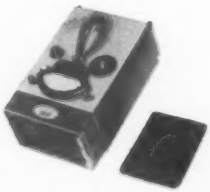

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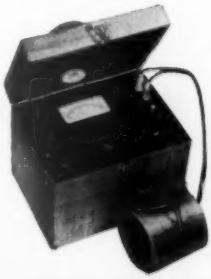

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| Filament Current | 10 | ma |
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| | | |
|---|---|---|
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| Filament Current | 10 | ma |
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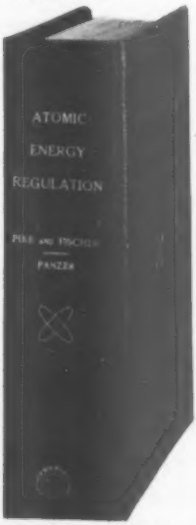


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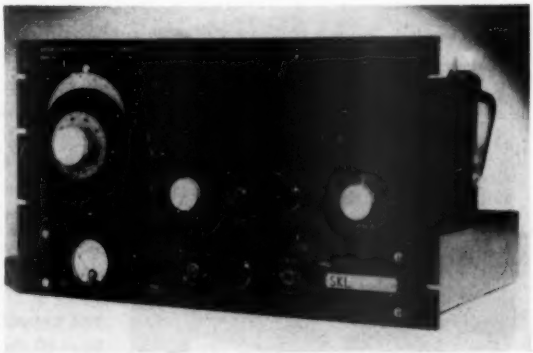


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3. Scintillation counting

Most nuclear research work today is done with Geiger and proportional counters—and probably will be for a long time to come. Yet the trend in research is toward the use of scintillation counters for all types of work.

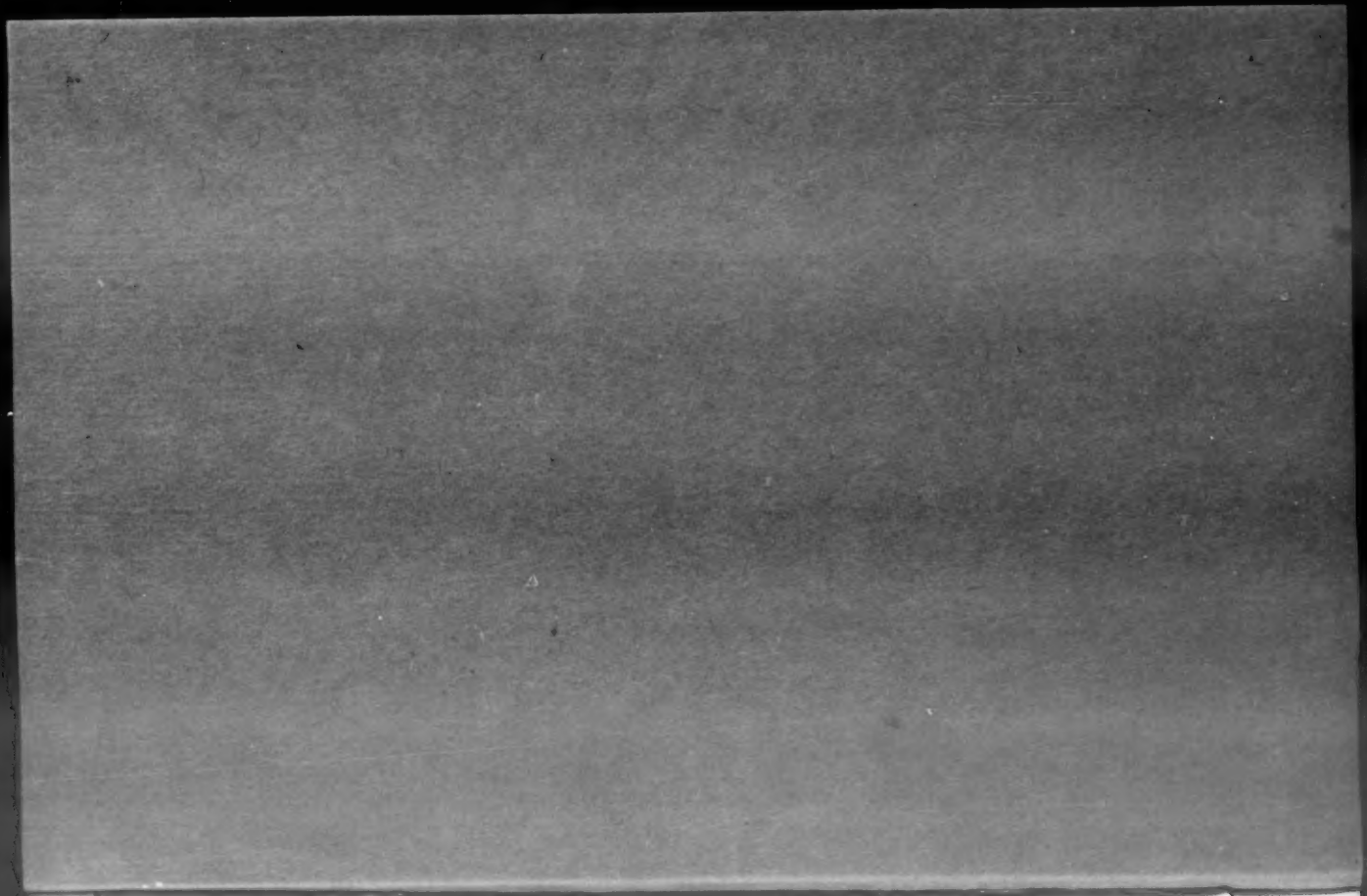
Nuclear's Model 162 Scaler is a highly adaptable instrument that will fit into your instrumentation plans . . . now and in the future. It is already in use in many laboratories with various kinds of counters.

Investigate the possibility of using this versatile instrument in your work. We will be glad to send full information on request.

*Model 162 Scaler used with a NUCLEAR Model D31 Geiger Counter and Model M2 Mount.*

*Model 162 Scaler used with a NUCLEAR Model D45 Alpha Proportional Counter.*

*Model 162 Scaler used with an experimental Scintillation Counter.*

**nuclear instrument & chemical corporation**

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